Department of Energy Technology

Net zero energy buildings integrated with multi-generation technologies: balance metrics, energy matching and economic analyses

Ayman Abdelhamed Mostafa Mohamed

Aalto University

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Abstract

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Abstract
The net zero energy building (NZEB) has been paid attention to internationally through last decade. Under the Finnish circumstances, there is a lack of knowledge and information that can help decision makers to define the NZEB consistently. In this thesis, some of the most important aspects of the NZEB and its applicability are investigated comprehensively. These aspects are the balance metric, energy matching capability, and economic viability. Integrating renewable energy systems with high efficient energy buildings to fulfill the NZEB balance is inevitable. More attention is paid to micro and small scale multi-generation systems including combined heat and power (CHP) technologies and combined cooling, heating, and power (CCHP). The multi-generation systems provide energy efficiency and environmental benefits due to generating on-site electrical and thermal power for a building simultaneously. The results show that regarding the NZEB balance metric, based on the Finnish data, the four common NZEB definitions are ordered according to the easiness of achievement as follows (1) NZEB-Finnish CO2 eq-emission (2) NZEB-Finnish primary energy (3) NZEB-cost and (4) NZEB-site. Domestic scale biomass CHP is not the best solution for the NZEB to replace a centralized power supply. Regarding the energy matching analysis, an overall weighted matching index (WMI) is developed. It combines the extended matching indices handling on-site energy systems involving electrical and thermal energy forms, energy conversions, various storages, and hybrid grid connections multiplied by certain weighting factors expressing the preferences of each. The WMI weighting factor calculation model is proposed physically and mathematically. An example for a micro-cogeneration application is conducted to illustrate the operability and comprehensiveness of using the WMI. The WMI's weighting factor calculation model proves that it is generic and applicable to hybrid micro-generation options. Regarding economic viability, the investigated biomass-based CHPs are economically viable only with high overall efficiency and low power-to-heat ratio due to both low investment and operational costs. The biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs.
This thesis shows that bioenergy-based CHP technologies could be promising integrated renewable energy systems in Finland achieving the NZEB based on the community level rather than on the single building level. To achieve the NZEB balance, CHP's characteristics have to be well optimized in order to minimize dependency on solar energy, maximize energy matching, and minimize life cycle costs. The upcoming legislation of nearly and net ZEB has to take the outputs of this thesis into consideration.

Keywords Zero energy building: Energy matching; Multi-generation; Cost optimality

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Preface

This doctoral thesis is based on a doctoral study conducted between 2011 – 2015 in HAVC department, Department of Energy Technology, School of Engineering, Aalto University, Finland. The study has been financially supported mainly by the School of Engineering, Aalto University. Moreover, the Finnish Academy (Grant numbers 272780 (2013–2015) and 140966 (2010–2013)), Aalto University SAGA project, Tekes RYM-Indoor Environment project (Grant number 704/11), and K.V. Lindholms Stiftelse have partially funded this doctoral study.

I would like to thank Prof. Kai Sirén and my instructor Dr. Ala Hasan for encouraging my research and for their valuable comments, advise, support, and guidance during the entire course of my studies in Finland. I consider myself extremely lucky for having found Dr. Ala Hasan as my instructor, not only he is an excellent scientist, but he is also a patient instructor.

I would like to thank my colleagues in the HVAC laboratory during these years. Special thanks for Dr. Mohamed Hamdy; my colleague in the same University in our home country Egypt. Special thanks for Dr. Ehab Foda for his help in my practical life in Finland. Thanks for Dr. Sunliang Cao, Dr. Juha Jokisalo, MSc. Lari Eskola, MSc, Janne Hirvonen's help in my doctoral studies. I would like to thank Dr. Simo Kilpeläinen and Matti Palonen for their important help with the laboratory work.

Thanks for the secretaries Mirka Seppälä, Saija Kaljunen, Seija Erander-Luukkanen, Jenni Lehtonen and Maija Pero who provided me lots of help in the administrative issues during my doctoral period.

Special thanks are due to my beloved mother, brothers, and sisters for their continuous support through my life. Special thanks of course are due to my loving wife, Sara Said for her unconditional love, support, and patience. I would like to dedicate my Ph.D thesis to the memory of my beloved father and my kids Karem and Alzahraa.

Finally, and above all, I would like to express my humble thanks to ALLAH (swt) for enlightening my way all the time, before, during, and after this thesis.

Ayman Mohamed
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List of original publications

I. Ayman Mohamed, Ala Hasan, Kai Sirén, Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives, Applied Energy, 114 (2014) 385-399. doi:10.1016/j.apenergy.2013.09.065 [1]

II. Sunliang Cao, Ayman Mohamed, Ala Hasan, Kai Sirén, Energy matching analysis of on-site micro-cogeneration for a single-family house with thermal and electrical tracking strategies, Energy and Buildings, 68, Part A (2014) 351-363. doi:10.1016/j.enbuild.2014.05.055 [2]

III. Ayman Mohamed, Sunliang Cao, Ala Hasan, Kai Sirén, Selection of micro-cogeneration for net zero energy buildings (NZEB) using weighted energy matching index, Energy and Buildings, 80, (2014) 490-503. doi:10.1016/j.enbuild.2014.05.055 [3]

IV. Ayman Mohamed, Mohamed Hamdy, Ala Hasan, Kai Sirén, The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions, Applied Energy, 152C (2015) 94-108. 10.1016/j.apenergy.2015.04.096 [4]

V. Ayman Mohamed, Ala Hasan, Kai Sirén, Cost optimal and net zero energy office buildings solutions using small scale biomass-based cogeneration technologies, proceedings of Building Simulation Applications - BSA 2015, 2nd IBPSA-Italy Conference, Bozen-Bolzano, Italy. 263-272, ISBN: 978-88-6046-074-5, Bozen-Bolzano University Press, Link of proceedings: http://bupress.unibz.it/en/buildings-simulation-applications-bsa-2015.html [5]

Author's contribution

The thesis author, Ayman Mohamed is the principle author of the four original publications (I, III, IV, and V). The papers, proposals, simulations, analysis of the data and writing of the papers are all conducted by him. Original publications II, III are dependent and related to each other. In publication II, the thesis author, Ayman Mohamed as the second author contributed in the survey of the available micro-cogeneration on the market, contributed in creating micro-cogeneration models, provided partial support for the analysis of the comparison between matching and net primary energy consumption with bio-fuel, and provided revisions during the writing of the paper, while the first author Sunliang Cao conducted most of the simulations, applied the energy matching topology on micro-cogeneration systems, analyzed the data, and wrote the paper. In publication III, the second author Sunliang Cao helped with the energy matching topology on micro-cogeneration system and helped in making micro-cogeneration models as used in publication II. In original publication V, the second author PhD Mohamed Hamdy helped by providing some cost data based on his previous cost-optimization analysis as well as provided revisions during the writing of the paper. The co-authors of Dr. Ala Hasan and Professor Kai Sirén provided supervision and revision for the research work of all the five publications.

Nomenclature and Abbreviations

AC	Absorption chiller
BSSP	Building service system package
CAV	Constant air volume
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
CO_2-eq	equivalent CO_2 emissions
COP	Coefficient of performance [-]
CS_{off}	Net off-site part of the cooling power sent to cold storage [kW_{th}]
CS_{on}	Net on-site part of the cooling power sent to cold storage [kW_{th}]
DC	District cooling
DC-SE	Direct combustion Stirling Engine
DH	District heating
DH-DC	District heating and district cooling systems
DH-VCR	District heating and vapor compression refrigeration system
DHW	Domestic hot water
D-ICE-VCR	Diesel-based internal combustion engine and vapor compression refrigeration system
dLCC	Incremental life-cycle cost [€/m^2]
dt	The time-step used in the research [h]
ECBCS	Energy Conservation in Buildings and Community systems
EEM	Energy efficiency measures
E_{exp}	Exported energy carrier
E_{imp}	Imported energy carrier
E_{off-c}	Off-site part of electrical power sent to electrical driven cooling machines [kWe]
E_{on-c}	On-site part of electrical power sent to electrical driven cooling machines [kWe]
E_{on-h}	Off-site part of electrical power sent to electrical driven heating machines [kWh]
E_{on-h}	On-site part of electrical power sent to electrical driven heating machines [kWh]
EPBD	Energy Performance of Building Directive
ES_{off}	Net off-site part of the electrical power sent to the electrical storage [kWe]
ES_{on}	Net on-site part of the electrical power sent to the electrical storage [kWe]
ETTR	Electrical to thermal ratio
EU	European Union
$f_{CHP,el}$, $f_{CHP,h}$	Allocated non-renewable primary energy factor of generated electricity and heat by the µ-CHP [kWh_{pr}/kWh_{site}]

F_{dc}	Interactive cooling power with the cooling grid [kWh]
F_{dh}	Interacted thermal heat power with the thermal heat grid [kWh]
F_{eg}	Interacted electrical power with the electrical grid [kWe]
f_F	Non-renewable primary energy factor of the fuel supplied to the μ-CHP [kWh_{pr}/kWh_{site}]
$f_{grid,el}$, $f_{grid,h}$	Non-renewable primary energy factor of electrical grid, heat grid, respectively [kWh_{pr}/kWh_{site}]
$f_{on\text{-}site,overall,el}$, $f_{on\text{-}site,overall,h}$	The on-site overall non-renewable primary energy factors of the generated electricity and heat by the on-site hybrid systems [kWh_{pr}/kWh_{site}]
FSOC	Fractional state of charge [-]
G(t)	Temporal on-site generated power [kW]
GC	Ground cooling
G_{c_th}	Cooling power generated by the on-site thermal energy production system [kW]
$G_{CHP,el}$	On-site electrical power generated by μ-CHP [kW_e]
$G_{CHP,h}$	On-site thermal heat power generated μ-CHP [kW_{th}]
GHG	Greenhouse gases
$G_{PV,el}$	On-site electrical power generated by PV modules [kW_e]
GSHP	Ground source heat pump
GSHP-GC	Ground source heat pump and free ground cooling
$G_{STC,h}$	On-site thermal heat power generated STC modules [kW_{th}]
$G_{tot,el}$	Total on-site electrical power generated by μ-CHP and PV modules [kW_e]
H/C	Heating/cooling
H/C-EGS	Heating/cooling energy generation system package
$H_{eoff\text{-}h}$	Generated heat power by the electrical driven heating machines by the off-site part of the electricity [kW_e]
$H_{eon\text{-}h}$	Generated heat power by the electrical driven heating machines by the on-site part of the electricity [kW_e]
$H_{off\text{-}c}$	Off-site part of the heating power sent to the thermally driven cooling machines [kW]
$H_{on\text{-}c}$	On-site part of the heating power sent to the thermally driven cooling machines [kW]
HS_{off}	Net off-site part of the thermal heat power sent to the thermal heat storage [kW_{th}]
HS_{on}	Net on-site part of the thermal heat power sent to thermal heat storage [kW_{th}]
HVAC	Heating, Ventilation, and air conditioning
HWST	Hot water storage tank
ICE	Internal Combustion Engine
ICE-AC	Biomass-based internal combustion engine with gasifier and absorption chiller system
ICE-VCR	Biomass-based internal combustion engine with gasifier and vapor compression refrigeration system
IEA	International Energy Agency
IFGT	Indirect Fired Gas Turbine
IFGT-AC	Biomass-based indirect fire gas turbine and absorption chiller system
IFGT-VCR	Biomass-based indirect fire gas turbine and vapor compression refrigeration system
L(t)	Temporal load power [kW]

l_c	Loss of on-site cooling power during the distribution process [kW]
LCC	life-cycle cost [€/m^2]
L_{cold}	Cooling load power [kW]
L_{el}	Electrical load power excluding the electrical load from the electrically driven heating and cooling machines [kW$_e$]
l_{el}	Electrical losses of on-site electrical power during the distribution process [kW$_e$]
L_h	Thermal heat load power excluding the thermal heat load from the thermal driven cooling machines [kW$_{th}$]
l_h	Thermal heat losses of on-site thermal heat power the during distribution process [kW$_{th}$]
LHV	Lower heating value [kWh/kg]
MS	Member states
mT	Micro-turbine
n_{50}	Number of air change per hour at 50 Pa indoor/outdoor differences [1/Pa]
NG	Natural gas
NG-ICE-VCR	Natural gas-based internal combustion engine and vapor compression refrigeration system
NG-mT-VCR	Natural gas-based micro-turbine and vapor compression refrigeration system
NRPE	Non-renewable primary energy
NZEB	Net zero energy building
nZEB	Nearly zero energy building
O&M	Operation and maintenance
OEF	On-site energy fraction [-]
OEFc	On-site thermal cooling energy fraction [-]
OEFe	On-site electrical energy fraction [-]
OEFh	On-site thermal heat energy fraction [-]
OEM	On-site energy matching
OEMc	On-site thermal cooling energy matching [-]
OEMe	On-site electrical energy matching [-]
OEMh	On-site thermal heat energy matching [-]
ORC	Organic Rankine Cycle
ORC-AC	Biomass-based organic Rankine cycle and absorption chiller system
ORC-VCR	Biomass-based organic Rankine cycle and vapor compression refrigeration system
P/H	Electrical power-to-heat ratio [-]
PB	Pellet boiler
PB-AC	Pellet boiler and absorption chiller system
PB-VCR	Pellet boiler and vapor compression refrigeration system
PE	Primary energy
PE_{import}, PE_{export}	The annual imported and exported primary energy of an energy carrier, respectively
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PH	Passive House
PV	Photovoltaic panel
Q_c	Thermal cooling capacity [kW]
Q_F	Total lower heating value [kWh/kg]
Q_h	Thermal heating capacity [kW]
RET	Renewable energy technology

SE	Stirling Engine
SE-AC	Biomass-based updraft gasifier with Stirling engine and absorption chiller system
SE-VCR	Biomass-based updraft gasifier with Stirling engine and vapor compression refrigeration system
SFP	Specific fan power [kW/(m^3/s)]
SH	Standard House
SHC	Solar Heating and Cooling
SHGC	Solar heat gain coefficient
SPC	Space cooling demand [kWh/m^{2}a]
SPF	Seasonal performance factor of the GSHP
SPH	Space heating demand [kWh/m^{2}a]
STC	Solar thermal collector
T	Temperature [C^o]
t	Time [h]
t_1	Starting point of the time span
t_2	Ending point of the time span
UG-SE	Updraft gasifier Stirling Engine
VAV	Variable air volume
VCR	Vapor compression refrigeration cooling system
w_1, w_2, w_3, w_4	Weighting factor of OEFe, OEMe, OEFh, and OEMh, respectively [-]
w_i	Weighting factor of the detailed matching indices [-]
WMI	Weighted matching index [-]
WP-SE	Wood pellet Stirling Engine
X_e, X_h	The proportions of the associated non-renewable primary energy with the generated electricity and heat, respectively [-]
$\eta_{CHP,el}$, $\eta_{CHP,h}$, $\eta_{CHP,overall}$	The electric, thermal and overall efficiencies of the µ-CHP, respectively [-]

1. Introduction

1.1 Background

The building energy needs in the European Union represent 40% of the final energy consumption [6]. This indicates the potential to make buildings highly energy efficient. The recast of the EU Directive on Energy Performance of Building (EPBD) specified that by the end of 2020, all new buildings shall be "nearly zero energy building" (nZEB) [7]. In the EPBD recast, the nZEB is defined as a building that has a very high energy performance and should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced onsite or nearby. Additionally, the International Energy Agency (IEA) joint Solar Heating and Cooling (SHC) Task 40 and Energy Conservation in Buildings and Community systems (ECBCS) Annex 52 titled "Towards Net Zero Energy Solar Buildings" made an international effort on the standardization of the Net Zero Energy Building (NZEB) definition [8]. The NZEB was simply defined as a building with greatly reduced energy needs through efficiency gains so that the balance of energy demand can be supplied with onsite or nearby renewable technologies on a yearly level [9].The energy efficiency measures (EEM) and renewable energy technologies (RET) together are the keys to fulfill the nZEB and NZEB requirements. Implementing such EEMs and RETs in a building is a challenging process to ensure that the building has the optimal design from energetic, environmental, and economical perspectives.

In the countries of northern Europe, dependency only on onsite solar energy as a renewable energy source (RES) to achieve the nZEB and NZEB definitions faces many obstacles, such as low solar irradiation and the mismatch between the energy production and consumption [10] and the limited area of roof and/or façade, primarily in dense city areas [11]. In Finland as shown in Figure 1, the CHP plants consumed 114 TWh of fuels by 2013 (about 72 % of the total fuel consumption used for heat and power production) [12]. Moreover, the abundance of biomass as the highest renewable energy source share (25 % in 2013[13]) which is considered a promising source beside wind power replacing the fossil fuel [14], encourages the focusing on and investigating the use of biomass-based combined heat and power (CHP) technologies as the main integrated renewable energy supply system in the building sector. The current thesis is a research effort seeking for the optimal design of integrated renewable energy systems and NZEBs. The following sub-sections discuss the background of the thesis topics.

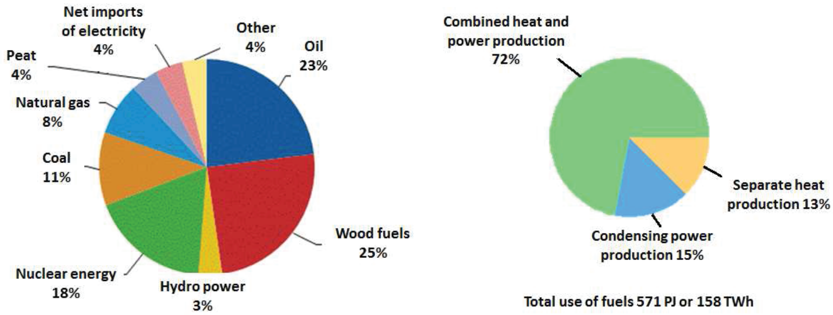

Figure 1 Share of total energy consumption in Finland 2013 (left hand side) [13]. Fuel use by production mode in electricity and heat production in Finland 2013 (right hand side) [12].

1.2 Net zero energy building definition

The NZEB definitions and the compatibility of proposed definitions with current national building codes and international standards are reviewed in [15]. Also, to put the NZEB definition in a consistent framework, some aspects must be identified as highlighted in [10]. These aspects are categorized into building system boundary, weighting system, NZEB balance, temporal energy match characteristics, and measurement and verification. Each has sub-criteria which has to be defined consistently. For example, the building system boundary means which energies are counted in the balance. The NZEB balance defines the type of balance used either between the imported and exported energies or energy demands and generation. , Which metric of balance will be applied primary energy, site energy, CO_2 eq-emission, or cost, depends on the weighting system. For imported and exported energy carriers, symmetric weighting factors will be used for the bi-direction grid or asymmetric ones. Moreover, the weighing factors can be time dependent or annually fixed, etc.

In the thesis and original publications, the NZEB is defined precisely to cover all abovementioned aspects. The building boundary is the building defined by its foot-print area, plus a small lot used to install any energy system, e.g., the solar system. If a shared biomass-based micro and small-scale CHPs are used, the building boundary extends to include the community of the building (Original publication I) and its shared systems as long as it is assumed that the energy generation system is a property of the building or the community. Thus, the building boundary includes the building and the energy generation systems as well.

According to the Finnish building regulation code D5-2012 [32], the typical operating energies are heating, cooling, ventilation, domestic hot water and lighting, HVAC equipment, and appliances. It should be emphasized that the weighting factors are used only for the operational energy, whereas the embodied energies are not taken into account. The balance between the exported and imported energies passing across the building boundary is considered. The net balance period is a year.

The weighted imported energy includes all delivered energies, summing all energy carriers each multiplied by its respective weighting factor. Symmetrical static weighting factors are considered (e.g., electricity and thermal heat energy), the weighting factors are equal for both imported and exported energies. The imported energy carriers used in this study are electricity from the grid, district heating, light oil, and biomass (wood pellet and wood chips) fuels. The electric grid is considered two-way energy grid in all original publications (I – V), where the weighted exported energy can be calculated by multiplying the exported electricity by its weighting factor. Additionally, in original publications II and III, it is assumed that the thermal heat grid can be two-way energy grid where it can receive the excess heat when the CHP operates under electrical tracking strategy. The electrical tracking strategy means that the CHP has to be ON with its nominal capacity to cover the electrical demand, therefore, there will be at sometimes excess by-product heat which should be exported to the thermal grid or dumped.

The annual import/export balance is achieved by using the net weighted energy depending on each NZEB definition. In order to achieve the NZEB balance, the annual net weighted energy should be equal to zero, according to the following Eqs. (1) - (3);

$$Weighted\ imported\ energy = \sum_{k=1}^{n} \left(\mathrm{E}_{\mathrm{imp,k}} \cdot \mathrm{f}_{\mathrm{k}}\right) \tag{1}$$

$$Weighted\ exported\ energy = \sum_{k=1}^{n} \left(\mathrm{E}_{\mathrm{exp,k}} \cdot \mathrm{f}_{\mathrm{k}}\right) \tag{2}$$

$$\begin{aligned} Net\ weighted\ energy \\ &= Weighted\ imported\ energy \\ &- Weighted\ exported\ energy = 0 \end{aligned} \tag{3}$$

where f is the weighting factor for each energy carrier, k refers to one energy carrier, and E_{imp} and E_{exp} are imported and exported energy carriers, respectively, summed from the hourly simulated value. The annual weighted imported energy accounts for all energy carriers imported to the building passing through the building boundary.

1.3 NZEB's investigated aspects in this thesis

1.3.1 NZEB metric of balance

Figure 2 is a sketch for the connection between buildings and energy grids showing relevant NZEB definition aspects. The NZEB metric is considered the key of the NZEB definition as long as it defines what exactly "zero" refers to. Mainly, four balance metrics are used to define NZEB by different twelve methodologies in [15]. The NZEB metric can be site energy (it can be also defined as delivered, end-use, or un-weighted energy), primary energy (PE), CO_2-eq emissions, or energy cost [16]. Moreover, exergy and emergy are proposed as metrics by [17] and [18], respectively. However, these exergy and emergy metrics are not common popular indicators. Many of the NZEB research studies used site energy [19, 20, 21, 22], primary energy [23, 24, 25], CO_2-eq emissions [21, 26, 27, 28], and/or energy cost [29] as the balance metric.

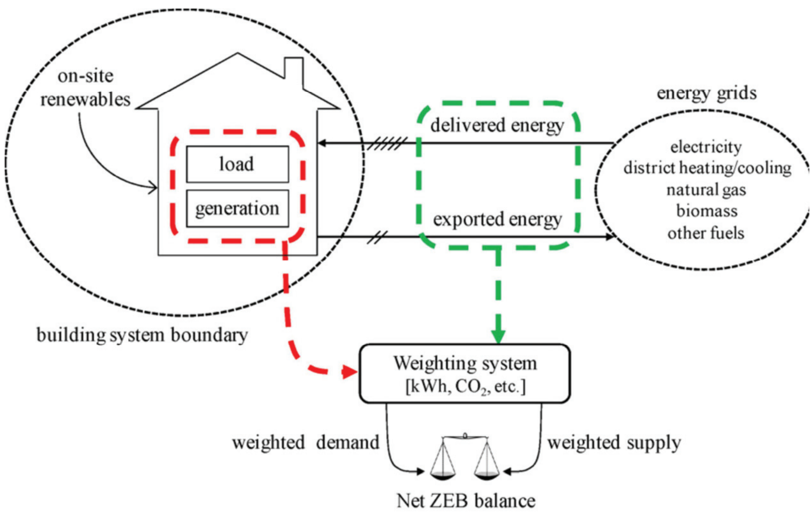

Figure 2 Sketch of connection between buildings and energy grids showing relevant NZEB definition aspects [10].

The national decision about the used metric varies from country to country. For example, the code for sustainable homes in the UK sets a target for all new homes to be zero carbon by 2016 [30]. Currently in Finland, the Finnish building regulation codes D3-2012 [31] and D5-2012 [32] indicate national primary energy factors that have to be used for any new building.

Investigation and comparison of the common suggested NZEB definitions based on their balance metrics obtained from national Finnish and international reference data is conducted in original publication I

1.3.2 Temporal energy match characteristics

Because the NZEB is grid connected, the energy matching capability between the on-site generation and the energy needs and/or the grid is one of the suggested criteria to be identified. Many factors and indicators were suggested to quantify the energy matching in the NZEB. For example, the mismatch compensation factor [33], and load-matching and grid interaction indicators [34, 35, 36] with respect to imported and exported energies. These indicators are applied for electricity, because the electric grid feed-in is currently the common scheme where exported electricity has to compensate the imported energies fulfilling the NZEB balance. Moreover, exported thermal energy to the district heating network was analyzed to examine the influences of excess heat production from NZEBs on Danish DH systems [37] and to optimize the ratio between the solar thermal collector (STC) and the photovoltaic (PV) from the energy matching point of view for the Swedish NZEB [38].

In [39,40], the basic indices of both the on-site energy fraction (OEF), which identifies the proportion of the load covered by the on-site generated energy, and the on-site energy matching (OEM), which identifies the proportion of the on-site generated energy that is used in the load rather than being dumped or exported, are extended to electrical, heating, and cooling matching indices, taking into account the energy conversion, storage, and hybrid grid connections.

Two basic matching indices; on-site energy fraction (OEF) and on-site energy matching (OEM) are mathematically defined by Eqs. (4) and (5).

$$OEF = \frac{\int_{t_1}^{t_2} Min\,[G(t); L(t)]dt}{\int_{t_1}^{t_2} L(t)\,dt}\ , 0 \leq OEF \leq 1 \tag{4}$$

$$OEM = \frac{\int_{t_1}^{t_2} Min\,[G(t); L(t)]dt}{\int_{t_1}^{t_2} G(t)\,dt}\ , 0 \leq OEM \leq 1 \tag{5}$$

Where G (t) and L (t) are temporal on-site generation power and load power, respectively, as shown in Figure 3, OEF is equal to the ratio of the area of section III to the overall areas of sections I and III, whereas OEM is equal to the ratio of the area of section III to the overall areas of sections II and III.

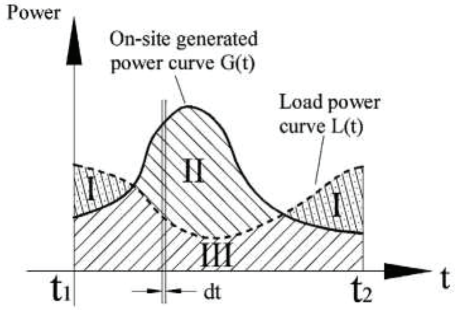

Figure 3 The main principle for the two basic indices OEF and OEM [39].

A topology was created in [39] to extend these two basic matching indices OEF and OEM to electricity; OEFe and OEMe, heating; OEFh and OEMh, and cooling; OEFc and OEMc matching indices taking into consideration the energy form, energy conversions, thermal and electrical storage, and hybrid grids connection (see Figure 4). The detailed mathematical formulas are presented by Eqs. (6) - (11). The abbreviations for the terms in these equations are listed and explained in the nomenclature of this thesis.

$$\mathrm{OEFe} = \frac{\int_{t_1}^{t_2} \mathrm{Min}[G_{elec}(t) - ES_{on}(t) - l_e(t);\ L_{elec}(t) + E_{off-h}(t) + E_{on-h}(t) + E_{off-c}(t) + E_{on-c}(t)]dt}{\int_{t_1}^{t_2}[L_{elec}(t) + E_{off-h}(t) + E_{on-h}(t) + E_{off-c}(t) + E_{on-c}(t)]dt} \tag{6}$$

$$\mathrm{OEFh} = \frac{\int_{t_1}^{t_2} \mathrm{Min}\left[G_{h\_th}(t) + H_{eon-h}(t) - HS_{on}(t) - l_h(t);\ L_{heat}(t) + H_{off-c}(t) + H_{on-c}(t)\right]dt}{\int_{t_1}^{t_2}[L_{heat}(t) + H_{off-c}(t) + H_{on-c}(t)]dt} \tag{7}$$

$$\mathrm{OEFc} = \frac{\int_{t_1}^{t_2} \mathrm{Min}\left[G_{c\_th}(t) + C_{hon-c}(t) + C_{eon-c}(t) - CS_{on}(t) - l_c(t);\ L_{cold}(t)\right]dt}{\int_{t_1}^{t_2} L_{cold}(t)dt} \tag{8}$$

$$\mathrm{OEMe} = \frac{\int_{t_1}^{t_2} \mathrm{Min}[G_{elec}(t);\ L_{elec}(t) + E_{on-h}(t) + E_{on-c}(t) + ES_{on}(t) + l_e(t)]dt}{\int_{t_1}^{t_2} G_{elec}(t)dt} \tag{9}$$

$$\mathrm{OEMh} = \frac{\int_{t_1}^{t_2} \mathrm{Min}\left[G_{h\_th}(t) + H_{eon-h}(t);\ L_{heat}(t) + H_{on-c}(t) + HS_{on}(t) + l_h(t)\right]dt}{\int_{t_1}^{t_2}[G_{h\_th}(t) + H_{eon-h}(t)]dt} \tag{10}$$

$$\mathrm{OEMc} = \frac{\int_{t_1}^{t_2} \mathrm{Min}\left[G_{c\_th}(t) + C_{hon-c}(t) + C_{eon-c}(t);\ L_{cold}(t) + CS_{on}(t) + l_c(t)\right]dt}{\int_{t_1}^{t_2}[G_{c\_th}(t) + C_{hon-c}(t) + C_{eon-c}(t)]dt} \tag{11}$$

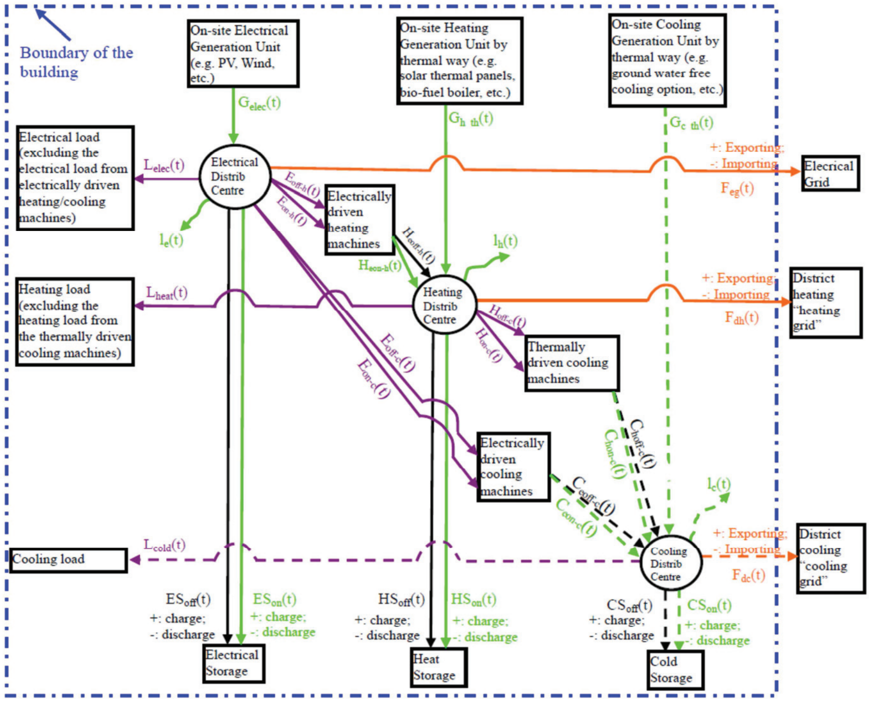

Figure 4 The topology of the extended matching indices for electricity, heating, and cooling [39]

In original publications II and III, comprehensive energy matching indices are formulated for the CHP application with and without installing photovoltaic panels (PV) or solar thermal collectors (STC). Specifically in original publication II, an overall energy matching index was defined as a weighting matching index (WMI). The WMI is the summation of matching indices multiplied by certain weighting factors wi, while the sum of the weighting factors is 1.0. The weighting factors wi can be selected to reflect various criteria such as economic benefits, environmental impacts, and political decisions. Original publication III answered the question how the weighting factors can be defined physically and mathematically in the case of the CHP under different operational strategies with and without installing PV and/or STC?

1.3.3 Economic viability of multi-generation technologies

Cost optimal and minimum energy performance solutions

The Energy Performance of Building Directive 2010/31/EU, (EPBD) recast [6] specified that by the end of 2020, all new buildings shall be "nearly zero-energy buildings" (nZEBs). As stipulated in this directive, all Member States (MS) shall ensure that a minimum energy performance requirement achieving cost-optimal levels has to be set using a comparative methodology framework. The methodology framework was published as EU supplementary EBPD recast in 2012 as "Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU " [41]. In May 2012, Finland submitted the minimum energy performance requirements for calculating cost-optimal levels report to the EU [42]. This report shows the cost-optimal of the minimum energy performance of new residential and commercial buildings built in accordance with the current Finnish building regulations D3-2012 [31] and D5 2012 [32] as well as existing buildings. As seen in the Finnish report [42], the multi-generation system including cogeneration of heat and power (CHP) and the tri-generation system (which is also defined as combined cooling, heating, and power (CCHP)) were not implemented.

Several studies in Europe focused on a combination of building energy performance and cost analysis. Since the EPBD recast has been published only recently, only a limited number of current studies refer directly to the objectives of the EPBD recast and related concepts. Several studies tried to investigate the cost-optimal levels of minimum energy performance requirements such as [43], [44], [45], and [46]. Regarding the calculation method used to evaluate the minimum energy requirements achieving cost-optimal levels within the comparative methodology framework, developed optimization techniques were presented by [47], [48], [49] applied to new buildings [50], [51], [52], [53], [54], and [55], and applied to the retrofitting of existing buildings. Regarding the national polices and perspectives compared with the EPBD requirements, an overview of the development and the current EPBD stage of implementation in Greece as well as the lessons learned and experiences gained are presented in [56].The adaptation of cost-optimal calculations under the national circumstances and Mediterranean climates of Turkey (as an EU Member Candidate) using an existing office building is presented in [57]. Most of the aforementioned studies investigated building elements without changing the energy supply systems or with limited conventional systems.

Extension to nZEB and NZEB from cost optimal and minimum energy performance solutions

Once the local cost optimal curves which refer to the solutions with minimum costs are obtained for all the studied systems including the multi-generation systems and conventional systems, two important associated solutions located on the cost-optimal curves, the local cost-optimal and minimum energy performance solutions, can be determined. The photovoltaic panel system (PV) is implemented by extending either the obtained local cost-optimal or the minimum energy performance solutions in order to find out the economic viability of achieving the nZEB and NZEB with the investigated multi-generation systems.

The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions are investigated in original publications IV and V.

1.4 The novelty of the thesis

This section summarizes the novelty of the thesis based on the original publications conducted during the author's doctoral study period. Original publication I has several findings. Firstly, arranging the NZEB definitions based on the easiness of achieving the NZEB balance under national Finnish and international circumstances. Secondly, though the importance of increasing the thermal energy efficiency of the buildings, it is shown that it has a reverse effect on the balance achievement of NZEB-Finnish emission and both NZEB-PE and NZEB-emission based on the international reference data for the biomass-based micro and shared CHPs. Lastly, a domestic scale biomass CHP is not the best solution for the NZEB to replace a centralized power supply. A local shared biomass CHP is better due to its characteristics (high overall efficiency and power to heat ratio). Environmentally, it helps with the reduction of air concentration of fine dust. The contributions of original publication II are as follows. The energy matching topology proposed in [39, 40] was developed to be able to handle the energy matching analysis of the micro-cogeneration system operated under thermal tracking with an electrical grid feed-in scheme and electrical tracking with a thermal heat grid feed-in scheme. The most important contribution is developing an overall matching index combining the extended indices by multiplying them by certain weighting factors expressing the preferences of each. Both the overall and extended indices can be used to analyze the matching situation from both the overall viewpoint and the detailed specific viewpoints. The contributions of original publication III is proposing a physical and mathematical model to calculate the weighting factor of the overall matching index based on the non-renewable primary energy (NRPE) factors (or other such as CO_2 equivalent emission factors and costs) of the different energy carriers crossing the building boundary. Besides that the proposed model aims basically to be applied on micro-cogeneration (μ-CHP) under thermal and electrical tracking strategies, reflecting the two opposite extreme matching situations in NZEB; load-matching priority and energy export priority strategies. The model is generic and can be used for hybrid micro-generation options. Original publications IV and V contribute by a comprehensive investigation of the economic and environmental viability of small scale biomass- and fossil fuel-based multi-generation technologies serving an office building in Helsinki, Finland. The investigation does not only look at the cost optimal and minimum energy performance solutions but it is extended to analyze nearly and net zero energy office buildings.

2. Investigation of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives (original publication I)

2.1 Objectives

In Section 1.3.1 the argument of the NZEB balance metric is highlighted. In this context, original publication I aims to compare the four most common NZEB metrics using weighting factors based on Finnish and international reference data. The comparison is conducted using twelve energy heating alternative systems, among them seven biomass-based standalone and shared combined heat and power (CHP) systems serving a single family house with two different building energy efficiency levels.

2.2 Investigated NZEB definitions

The four most common metrics used as weighting systems are: primary energy (PE), site energy, CO_2-eq emissions, and energy costs. The four NZEB definitions investigated in this study are net zero primary energy building based on Finnish weighting factors (NZEB-Finnish PE), net zero site energy building (NZEB-site), net zero emission building based on Finnish weighting factors (NZEB-Finnish emission), and net zero energy cost building (NZEB-cost). Additional NZEB definitions using international weighting factors based on IEA SHC 37 Subtask B [58] are investigated (NZEB-IEA-PE and NZEB-IEA-emission). For each definition, the weighting factors of the energy carriers are shown in Table 1.

Table 1 The Finnish and international weighting factors for different energy carriers (original publication I)

NZEB definition	Unit	Weighting factors					Ref
		Ele.	DH	wood pellet & wood chips	Light oil	Local renewable sources (solar)	
Finnish weighting factors							
NZEB-Finnish PE	kWh_{pe}/kWh_{end}	1.7	0.7	0.5	1.0	0	[31]
NZEB-site	kWh/kWh_{end}	1	1	1	1	0	[9]
NZEB-Finnish emission	g_{co2} / kWh_{end}	456	226	18	267	0	[59]
NZEB-cost	c/ kWh_{end}	13.24	6.29	5.47	10.66	0	[60]
International weighting factors							
NZEB–IEA-PE	kWh_{pe}/kWh_{end}	2.35	0.77	0.14/0.06	1.3	0	[61]
NZEB-IEA-emission	g_{co2} / kWh_{end}	430	241	43/35	311	0	[61]

2.3 Heating alternative systems

The study analyzes five conventional energy systems and seven biomass-based standalone and shared CHP systems. The conventional heating systems are electric heating system, district heating (DH), ground source heat pump (GSHP), light oil, and wood pellet boilers. The biomass-based micro and small-scale CHP systems are a 1.4 kWe wood pellet Stirling engine (WP-SE) standalone biomass-based micro CHP, five shared biomass-based micro and small-scale CHP systems; a 35 kWe Direct Combustion Stirling Engine (35 kWe DC-SE), a 35 kWe Updraft Gasifier Stirling Engine (35 kWe UG-SE), a 100 kWe Indirect Fired Gas Turbine (100 kWe IFGT), a 30 kWe with Internal Combustion Engine coupled with gasifier (30 kWe ICE) (the woodchip is converted to combustible gases by heating in a reduced oxygen environment in a downdraft gasifier after which the gas is cleaned and combusted in a modified compression ignition engine), and a 0.86 kWe direct combustion Organic Rankine Cycle (0.86 kWe ORC) (which was tested experimentally with relatively low expander efficiency and low alternator efficiency), and a domestic scale polymer electrolyte membrane fuel cell (PEMFC) that operates with hydrogen produced via an on-site central biomass gasification plant. Table 2 shows the performance of the standalone and shared biomass CHP and the fuel cell systems. In order to avoid significant amounts of heat loss which might exceed the building heat thermal needs, all CHPs are operated in thermal tracking operation where it is the common control strategy for CHPs units. The thermal tracking strategy means that whenever there are heating demands, the CHP has to be on to cover that heating demand as much as possible. Meanwhile, the produced electricity was a by-product. The numbers of the standard houses (SH) and passive houses (PH) are calculated by dividing the thermal output including the distribution losses of the thermal network by the peak thermal demand of the house. More detailed descriptions of the energy systems characteristics can be found in original publication I.

Table 2 Performance of standalone and shared biomass CHP and fuel cell systems (original publication I)

Description	Number of houses		Electric power P_e (kW)	Thermal output H_{th} (kW)	Electrical efficiency η_e%	Thermal efficiency η_{th}%	Overall efficiency η_{tot}%	Power / Heat P/H
	standard	passive						
1.4 kWe wood pellet SE	1	1	1.38	5.4	14.3	57.8	72.1	0.256
35 kWe direct combustion SE	44	67	35	215	12.0	74.0	86.0	0.16
35 kWe updraft gasifier SE	30	45	35	145	18.0	72.0	90.0	0.24
100 kWe direct combustion IFGT	41	62	100	200	28.0	56.0	84.0	0.5
30 kWe gasifier, ICE	16	25	30	80	23.0	61.0	84.0	0.377
0.86 kWe biomass fired ORC	9	14	0.86	47.26	1.41	78.69	80.1	0.0184
The hydrogen based PEMFC	1	1	2.70/1.8	4.80/3.2	15.32	27.28	42.60	0.56

2.4 Building description

The energy supply systems are connected to a single family house located in Helsinki, Finland, with two energy efficiency levels: a standard house and a passive house. The standard house (SH) is defined in accordance with the energy level of the Finnish building regulation codes D3-2012 [31] and D5-2012 [32]. The passive house (PH) is defined in accordance with the Finnish Association of Civil Engineers [RIL 249-2009] [62], which defines the requirements of a passive house in Finland (see Table 3 and Table 4). All simulated cases (the buildings integrated with the energy supply options) are performed by Trnsys 17 software [63].

The simulated results of the thermal and electric demands of the SH and PH are shown in Table 5. The simulation results indicate that, the space heating demand and DWH demand are reduced by 67.4% and 41.8% between SH to PH, respectively. The total thermal demand is reduced by 57%. The reduction of electric demand is only 5% which is associated with the use of a highly efficient energy ventilation system. The thermal peak demands of the SH and PH are 5.9 kW and 3.5 kW, respectively.

Table 3 Characteristics of the single family house envelope (original publication I)

House description	Standard house	Passive house
Thermal transmittance U- value (W/m2.K) of the thermal envelope		
External wall	0.169	0.074
External roof	0.09	0.065
Ground floor layer with soil layer below	0.16	0.07
Windows, doors and exit doors	0.98	0.68
Air tightness n50 *(1/h)*	2.0	0.6

Table 4 Features of the mechanical ventilation system and DHW needs (original publication I)

House description	Standard house	Passive house
Air flow rate ACH for the occupied zones(Whole year)	0.7 all rooms, 0.98 living room	0.7 all rooms, 0.98 living room
Heat recovery efficiency	60 %	85 %
Specific fan power of the mechanical ventilation (SFP) kW/(m3/s)	2	1.5
DHW daily flow(l/person per day)	62	37.6

Table 5 The simulated thermal and electric demands of the standard and passive houses (original publication I)

House description	**Standard house**	**Passive house**
Thermal demands in (kWh/m^2a)		
Radiator heating	51.06	18.54
Heating demand of mechanical ventilation	13.33	2.43
Space heating demand	*64.39*	*20.97*
DHW demand	38.03	22.13
Total thermal demand	*102.42*	*43.10*
Electric demands in (kWh/m^2a)		
Electric consumption of the HVAC systems	7.07	5.50
Electric consumption of the lighting	7.01	7.01
Electric consumption of the appliances	15.77	15.77
Total electric demand	**29.85**	**28.28**

2.5 NZEB balance

The NZEB definition is defined precisely in Section 1.2. The building boundary and imported/exported energy carriers regarding a single house and a community of houses are presented in Figure 5. In order to achieve the NZEB balance, the annual net weighted energy should be equal to or less than zero as given by Eqs. (1) - (3).

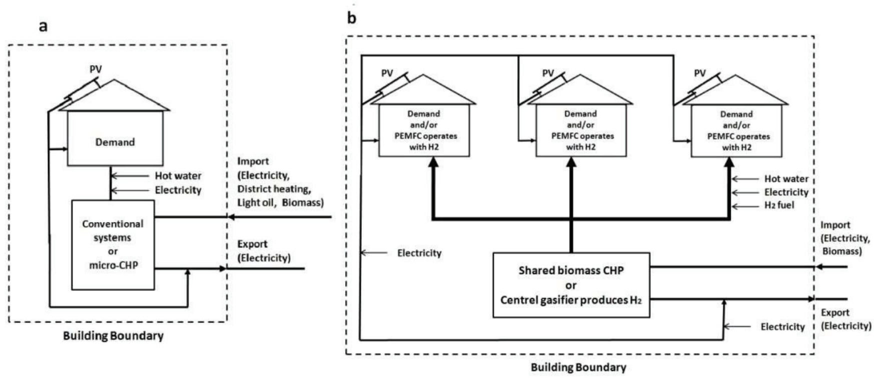

Figure 5 Building boundary and imported/exported energy carriers of (a) a single house and (b) a community of houses (original publication I)

2.6 On-site supplementary system

All heating systems mentioned in Section 2.3 are investigated using the weighting factor of each NZEB metric. Whenever the NZEB balance was not achieved, an on-site supplementary system was installed to produce electricity from solar energy with zero weighting factors for all NZEB definitions (Table 1). To fulfill the NZEB balance, the photovoltaic (PV) modules are installed to offset the difference between the imported and exported electricity by producing electricity on-site. The orientation of the PV modules is selected to face south with a tilt angle of 45 °. The electricity production after the inverter of a one square meter of PV is 93.0 kWh/a, which is equivalent to 0.62 kWh/a per floor area of the house. These results are obtained by simulating the PV system with Trnsys 17 using Type194 based on the five-parameter equivalent circuit model. Other PV technical description and its electricity production can be found in original publication I.

2.7 Finnish NZEB definitions' comparison

Figure 6 shows the imported and exported weighted energies for all energy systems and all Finnish NZEB definitions. The sum of imported weighted energies is illustrated on the X-axis. The Y-axis shows the exported weighted energy related only to the surplus electricity of the CHP systems production. Once the represented point of any case is below the zero balance line, the on-site electricity production must be supplied by the PV system to achieve the NZEB balance. Table 6 shows the PV area required to achieve the balance of all the NZEB definitions in case of the SH and PH. The example shown in Figure 6-a shows the effect of the self-matching due to utilizing part of the PV electricity production which reduces the imported PE for the case of the shared 100 kWe IFGT with the community of SHs. The Finnish PE limit defined in the building codes D3 [31] of 159.5 kWh/m^{2}a for a 150 m^2 floor area is shown in Figure 6-a. The imported Finnish PE must be lower than the Finnish PE limit to be accepted.

As shown in Figure 6-a, it can be noticed that without installing any PV, the SH with electrical heating, light oil boiler and PEMFC cases are not appropriate as energy systems since their corresponding imported Finnish PEs are higher than the defined limit. The reasons are the high weighting factors of electricity (1.7), light oil (1.0), and very low overall efficiency of 42.6 % of the PEMFC based on biomass fuel, respectively. When the house becomes PH, all the energy systems are within the imported PE limits. It is also can be noticed that the 100 kWe IFGT has the lowest PV area required to achieve the NZEB-Finnish emission, NZEB-Finnish PE, and NZEB-cost balances due to its high P/H ratio and overall efficiency. From both Figure 6 and Table 6, the NZEB definitions can be arranged in the following order according to the easiness of achieving of the annual balance: (1) NZEB-Finnish emission (2) NZEB-Finnish PE (3) NZEB-cost and (4)

NZEB-site. This order is due to the ratio of the weighting factors of any energy carrier to that for grid electricity (Here, the electrical grid is the only two way energy flow considered). Moreover, reducing the thermal energy demand of the building (PH instead of SH) is a step toward achieving NZEB-Finnish PE, NZEB-cost, and NZEB-site for all energy systems. On the contrary, a reverse effect on the balance achievement of NZEB-Finnish emission for the biomass-based micro and shared CHPs is observed. The reason has two attributes. Firstly, electrical demand of the PH does not have the same reduction relative to the SH as the thermal demand. The electric reduction that takes place in the PH is only related to the use of a highly efficient energy ventilation system with only 5% reduction, while the thermal reduction is 57%. This means that while the operational strategy of the CHPs is thermal tracking, the possibility of the SH to produce electricity (whether utilized by the house demand and/or exported to the grid), is higher than for the PH. Secondly, the ratio of the weighting factors of electricity to biomass is very high in this definition.

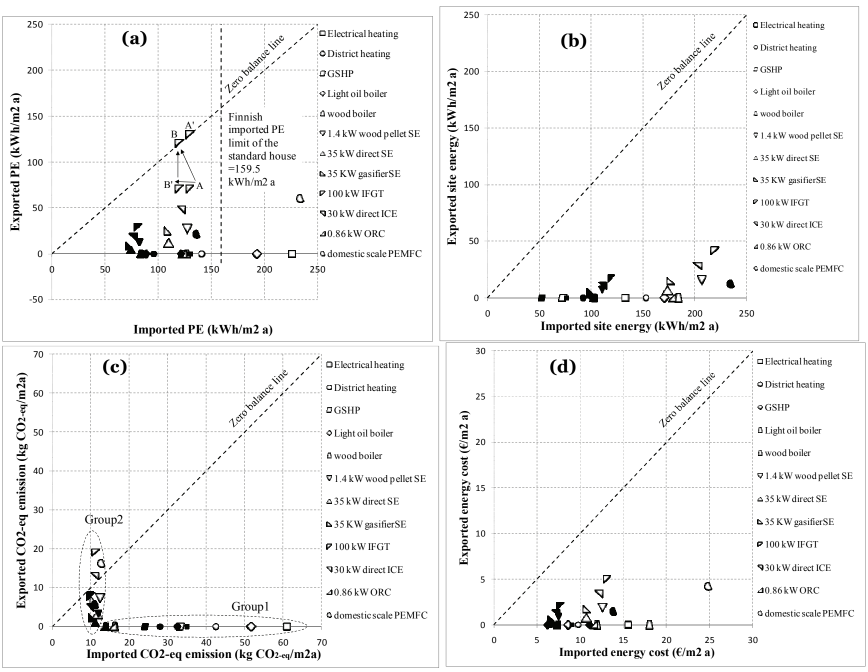

Figure 6 Imported/exported weighted energy for all studied cases (a) NZEB-Finnish PE, (b) NZEB-site, (c) NZEB-Finnish emission, (d) NZEB-cost. (Unfilled and filled marks are the SH and PH cases, respectively) (Original publication I)

Table 6 PV area required to achieve the balance required by the four NZEB definitions for the SH and PH (Original publication I).

Energy Systems	PV area required of standard house (m^2)				PV area required of passive house (m^2)			
	NZEB-Finnish PE	NZEB-site	NZEB-Finnish emission	NZEB- cost	NZEB-Finnish PE	NZEB-site	NZEB-Finnish emission	NZEB- cost
Electrical Heating	215	215	215	215	124	124	124	124
District heating	134	247	150	146	91	149	99	97
Ground source heat pump	117	**<u>117</u>**	117	117	85	**<u>85</u>**	85	85
Light oil boiler	183	275	182	232	115	162	115	140
Wood boiler	121	297	57	151	80	167	49	95
1.4 kWe wood pellet Stirling engine	95	308	18	131	67	167	30	84
35 kWe direct combustion, Stirling engine	94	270	31	124	68	155	36	82
35 KWe updraft gasifier, Stirling engine	80	261	14	110	61	152	28	76
100 kWe direct combustion indirect fired gas turbine	**<u>56</u>**	287	**<u>0</u>**	**<u>95</u>**	**<u>49</u>**	165	**<u>8</u>**	**<u>69</u>**
30 kWe gasifier Internal combustion engine	70	282	0	106	56	162	18	74
0.86 kWe organic Rankine cycle	117	288	56	146	79	165	48	94
Domestic scale PEMFC connected to shared gasifier	165	655	0	247	109	358	19	151

Under-lined values indicate the minimum PV area required for each NZEB definition

2.8 Finnish vs international weighing factors

The difference between the primary energy factors of Finland and the International Energy Agency (IEA) is related to the relative portion of electricity production by RESs in the national and international grid. As shown in Table 7, for the NZEB-IEA-PE, the PE values of the conventional thermal energy systems decrease with changing a house from a SH to a PH, while the PE values of the biomass CHP systems increase similar to the case of NZEB-Finnish emission with biomass CHP systems. Additionally, the biomass CHP systems; the 100 kWe IFGT, the 30 kWe gasifier ICE and the domestic scale PEMFC with the SH are all plus NZEB-IEA-PE. It can be concluded that the achievement of the NZEB-IEA-PE needs a PV area which is always less than the NZEB-Finnish PE with both the SH and PH.

Based on the CO_2-eq emissions factors shown in Table 1, it can be noticed that, except for electricity, the IEA CO_2-eq emissions factors of the other energy carriers are higher than the Finnish ones. Therefore, the required PV areas to achieve the NZEB-Finnish emission balance are smaller than that for the NZEB-IEA emission balance regarding the same energy system and the house energy demand level, as indicated in Table 7. It can be concluded that achieving the NZEB-Finnish emission balance is easier than the NZEB-IEA emission balance for all the studied energy systems with both the SH and the PH.

Table 7 Comparison of the PV area required to achieve the balance for the NZEB primary energy and $CO_{2\text{-eq}}$ emission definitions based on Finnish and international reference data for the SH and PH.

Energy Systems	PV area required of standard house (m^2)				PV area required of passive house (m^2)			
	NZEB-Finnish PE	NZEB-IEA-PE	NZEB-Finnish emission	NZEB-IEA-emission	NZEB-Finnish PE	NZEB-IEA-PE	NZEB-Finnish emission	NZEB-IEA-emission
Electrical Heating	215	215	215	215	124	124	124	124
District heating	134	118	150	163	91	83	99	106
Ground source heat pump	117	117	117	117	85	85	85	85
Light oil boiler	183	176	182	214	115	111	115	131
Wood boiler	121	62	57	73	80	51	49	56
1.4 kWe wood pellet Stirling engine	95	25	18	37	67	33	30	39
35 kWe direct combustion, Stirling engine	94	27	31	41	68	34	36	41
35 KWe updraft gasifier, Stirling engine	80	11	14	25	61	27	28	34
100 kWe direct combustion indirect fired gas turbine	56	0	0	0	49	5	8	15
30 kWe gasifier Internal combustion engine	70	0	0	6	56	16	18	25
0.86 kWe organic Rankine cycle	117	52	56	66	79	47	48	53
Domestic scale PEMFC connected to shared gasifier	165	0	0	17	109	14	19	34

2.9 Summary

Section 2 can be summarized as follows. The NZEB definitions are ordered based on the easiness of achieving the NZEB balance under national Finnish circumstances as follows: NZEB-PE, NZEB-site, NZEB-emission and NZEB-cost. Though it is important to increase the thermal energy efficiency of buildings, it is shown that it has a reverse effect on the balance achievement of NZEB-Finnish emission and both NZEB- PE and NZEB-emission requirements based on the international reference data for the biomass-based micro and shared CHPs. A domestic scale biomass CHP is not the best solution for the NZEB to replace a centralized power supply. A local shared biomass CHP is better due to its characteristics (high overall efficiency and power to heat ratio).

3. Energy matching of on-site cogeneration system under thermal and electrical tracking strategies using weighted energy matching WMI (Original publication II and III)

3.1 Objective

Depending not only on the electric grid feed-in scheme but also the thermal grid feed-in scheme, which is being developed in some EU countries, the μ-CHP as an on-site generation option is analyzed based on extended OEF and OEM factors for both electricity and thermal energy in original publication II. The μ-CHP is analyzed under two different control strategies: thermal tracking with the electrical grid feed-in scheme, and electrical tracking with the thermal grid feed-in scheme. Additionally, a weighted matching index (WMI) is developed to show the matching situations instead of the specified extended indices by summing the detailed index multiplied by certain weighting factors, expressing the preferences of each.

Original publication III aims to answer the following question: how can the weighting factors w_i of the weighted energy matching factor (WMI) developed in Original Publication II be defined physically and mathematically in the case of a μ-CHP operated under thermal and electrical tracking, with and without installing PV and/or STC modules fulfilling the NZEB balance? A new model is suggested to calculate the weighting factors of the WMI for the previous situations, reflecting the two opposite extreme matching situations in the NZEB load-matching priority and energy export priority strategies. The load-matching priority strategy means the self-consumption of the on-site generated energy has to be maximized [10]. Without seasonal storage where the building cannot depend totally on-site energy generation, there is essential need to export energy to the connected grid to compensate for the imported energies. This is the so called energy export priority strategy energy. The export priority strategy means that the on-site generated energy has to be exported regardless of the building's load or storage possibilities, aiming to fulfill the balance with the imported energy [10].

3.2 Detailed energy matching indices

In Section 1.3.2, the temporary energy matching characteristics are surveyed. Among the quantitative indices assessing the energy matching, the recent detailed topology and their detailed energy matching indices [39, 40] are chosen to analyze the matching capability of the on-site μ-CHP. As long as there is no cooling demand in this study, only the detailed matching indices OEFe, OEMe for electricity and, OEFh, OEMh for heating energy are chosen. The basic topology as well as the basic equations Eqs. (6) - (11) are simplified to be matched with the aim of this study, focusing on the μ-CHP. Figure 7 shows the simplified topology for the on-site μ-CHP (original publication II) including photovoltaic (PV) and/or flat plat solar thermal collector (STC) modules (original publication III). The simplified equations of the detailed matching indices of the on-site μ-CHP (original publication II) with additional PV and/or STC modules installation, fulfilling the NZEB balance (original publication III) are given in Eqs. (12) - (15). The abbreviations for the terms in these equations are listed and explained in the nomenclature of this thesis.

$$OEFe = \frac{\int_{t_1}^{t_2} Min\left[G_{mCHP,elec}(t) + G_{PV,elec}(t) - ES_{on}(t) - l_e(t); L_{elec}(t) + E_{off-h}(t) + E_{on-h}(t)\right]dt}{\int_{t_1}^{t_2}[L_{elec}(t) + E_{off-h}(t) + E_{on-h}(t)]\,dt} \tag{12}$$

$$OEFh = \frac{\int_{t_1}^{t_2} Min\left[G_{mCHP,h\_th}(t) + G_{STC,h\_th}(t) + H_{eon-h}(t) - HS_{on}(t) - l_h(t); L_{heat}(t)\right]dt}{\int_{t_1}^{t_2} L_{heat}(t)\,dt} \tag{13}$$

$$OEMe = \frac{\int_{t_1}^{t_2} Min\left[G_{mCHP,elec}(t) + G_{PV,elec}(t)\right]; L_{elec}(t) + E_{on-h}(t) + ES_{on}(t) + l_e(t)\right]dt}{\int_{t_1}^{t_2}[G_{mCHP,elec}(t) + G_{PV,elec}(t)]\,dt} \tag{14}$$

$$OEMh = \frac{\int_{t_1}^{t_2} Min\left[G_{mCHP,h\_th}(t) + G_{STC,h\_th}(t) + H_{eon-h}(t); L_{heat}(t) + HS_{on}(t) + l_h(t)\right]dt}{\int_{t_1}^{t_2}[G_{mCHP,h\_th}(t) + G_{STC,h\_th}(t) + H_{eon-h}(t)]dt} \tag{15}$$

As shown in Figure 7, according to original publication II, the whole topology is composed of the electrical part and the thermal heat part, each of which is centered on a distribution center. Each distribution center is connected with a generation box, a load box, a storage box, and a grid box. The electrical and thermal energy parts are interfaced by an electrically driven heating machine, which converts electrical power into thermal heat power. According to the control principle for μ-CHP, which will be described in Section 3.5, auxiliary electrical heaters are used in the thermal tracking strategy. Thus, in this study, the electrically driven heating machine is the electrical heater, while $H_{eoff-h}(t)$ and $H_{eon-h}(t)$ are directly equal to $E_{off-h}(t)$ and $E_{on-h}(t)$, respectively.

The simplified topology for extended matching for μ-CHP coupled with PV and STC modules is specified according to original publication III. B1 refers to the building boundary including the on-site generation options μ-CHP, PV modules, and STC modules. All energy carriers crossing the boundary B1 should be taken into account in the NZEB balance. B2 refers to an imaginary boundary where all energies in electrical or thermal forms are categorized as on-site or off-site. It is obvious that the matching analysis does not deal with fuel crossing the building boundary B1 (e.g. the fuel of the μ-CHP), but it deals with the electrical and thermal heating energies (flow across boundary B2) as long as the main goal is to evaluate the interaction between the building needs, on-site generation, and/or the electrical and thermal grids with possibilities for export (or damping the surplus) [39]. Also, for the conversion process as shown by the electrically driven heating, the analysis follows the energy carrier, since it is electrical, and the thermal heating energies within the B2.

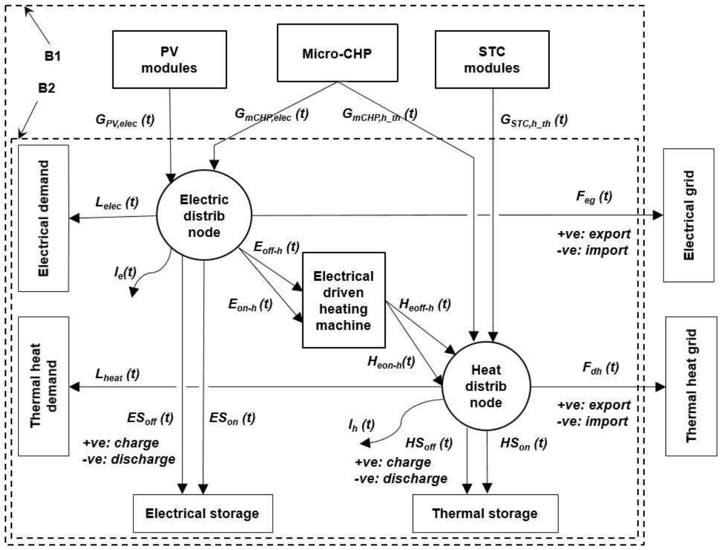

Figure 7 Simplified topology for extended matching specified for μ-CHP, coupled with PV and STC modules. Note that the electrical demand excludes the electrical needs of the electrical-driven heating machines. (Original publication III)

3.3 Developed overall criteria

Instead of the detailed comprehensive energy matching indices for electrical, heating, and cooling energy forms, an overall index is developed and suggested to reflect the overall matching capability where all detailed matching aspects are considered. This overall developed matching index is defined by weighted energy matching (WMI) because of the principle of how it is calculated. It can be formulated in general additive formula as shown by Eq.

(16). As shown in the detailed Eq. (17), the WMI is the sum of six terms: each term is calculated by multiplying one of the six extended matching indices by certain weighting factors, w_i, while the sum of these weighting factors is 1.0. These weighting factors show the priorities of preferences on the six extended matching indices. In this way, the WMI essentially reflects the overall matching situation by putting preferences on certain matching aspects. The selection of the weighting factors can be based on various considerations, such as the environmental impact, political decisions, and economical benefit. In this thesis, original publication II focuses mainly on the development of the concept of the weighted matching index, whereas how the weighting factors can be calculated is the main objective of original publication III.

$$WMI = \sum_{i=1}^{n} [w_{(2i-1)} * OEF(i) + w_{(2i)} * OEM(i)] \qquad n = 3;\ 0 \leq WMI \leq 1 \tag{16}$$

where

$$OEF(x) = \{OEFe, OEFh, OEFc\}$$
$$OEM(x) = \{OEMe, OEMh, OEMc\}$$

In detail, the WMI is formed as following

$$WMI = w_1 OEFe + w_2 OEMe + w_3 OEFh + w_4 OEMh + w_5 OEFc + w_6 OEMc$$
$$\sum_{i=1}^{6} w_i = 1, \qquad 0 \leq w_i \leq 1, \qquad 0 \leq WMI \leq 1 \tag{17}$$

Since in this thesis, only four detailed matching indices are dealt with; OEFe, OEMe for electricity, and OEFh, OEMh for heating energy, the WMI is formulated as follows in Eq. (18)

$$WMI = w_1 OEFe + w_2 OEMe + w_3 OEFh + w_4 OEMh$$
$$\sum_{i=1}^{4} w_i = 1, \qquad 0 \leq w_i \leq 1, \qquad 0 \leq WMI \leq 1 \tag{18}$$

It is worth mentioning that OEF and OEM are independent of each other. The values of both indices according to their definition depend on the control strategy of the on-site generation system and the demand profile. For instance, for a CHP system, fixed thermal and electrical demand profiles are assumed, the proportion of the thermal and electrical load covered by the on-site generated energy i.e. OEFh and OEFe, and the proportion of thermal and electrical the on-site generated energy that is used in the load i.e. OEFh and OEMe values will vary according to the applied operation strategy such as always on, seasonally on, thermal and electrical tracking strategies.

3.4 Simulation tools, single-family house, and NZEB definition

The developed WMI is implemented for the matching assessment of the μ-CHP unit for a single family house. The single family house is the same standard house used in original publication I, located in Helsinki, Finland. The house and the systems are simulated by Trnsys 17 software [63]. The annual heating of the standard house including AHU, space, and DHW heating is 100.3 kWh/m^{2}a with a peak of 6.0 kW. The electrical demand including ventilation fan, lighting, and appliances (excluding the electrical consumption of the circulating pump of the μ-CHP and auxiliary electrical heaters) is 29.9 kWh/m^{2}a with a peak of 5.6 kW (Original publication II and III).

The NZEB definition is defined precisely in Section 1.2. Thus in original publication III, the building boundary and imported/exported energy carriers regarding a single house is presented by boundary B1 in Figure 7. In order to achieve the NZEB balance, the annual net weighted energy (net primary energy in Original publication III) should be equal to zero as given by Eqs. (1) - (3).

The non-renewable primary energy (NRPE) factors of grid electricity, district heating, NG, bio-syngas, and solar energy are given in Table 8. The NRPE factors of district heating, NG, and solar energy are obtained from [58], while the NRPE factor of bio-syngas produced from forest residue and electricity is obtained from [64].The μ-CHP operates with its nominal capacity (full load), which is in accordance with original publication II and [65].

Table 8 The non-renewable primary energy (NRPE) factors of the energy carriers. (Original publication III)

Weighting system	Unit	NRPE factors				
		Electricity	District heating	Natural gas	Bio-syngas	Solar energy
Primary energy	kWh_{pr}/kWh_{site}	2.23	0.77	1.14	0.17	0.00

3.5 Thermal and electrical tracking operation strategies of the μ-CHP

The μ-CHP can be operated under two basic control strategies; thermal and electrical tracking strategies. Figure 8 presents the schematic diagram of the control strategy, thermal connections of the μ-CHP, and electrical connections of both the μ-CHP and the PV modules (when used in original publication III) under the thermal tracking strategy. Figure 9 presents the schematic diagram of the control strategy, electrical connections of the μ-CHP, and the thermal connections of both the μ-CHP and the STC modules (when used in original publication III) under the electrical tracking strategy. The maximum allowed heat transfer fluid temperatures (it is water in this researcher) returning to and supplying from the μ-CHP are set at 55 °C and 65 °C, respectively, to match the consideration of the DHW set-point temperature of 55 °C.

As shown in Figure 8 for the thermal tracking strategy, the μ-CHP is connected to a hot water storage tank (HWST). In the thermal tracking strategy, the switch of the μ-CHP and the pump is controlled by the temperature of the heat transfer fluid at the bottom of the tank (T_1): if the T_1 is higher than 55 °C, both the μ-CHP and the pump will be turned off to prevent the return temperature (T_2) from exceeding 55 °C; whereas if the T_1 is below 55 °C, both the μ-CHP and the pump will be turned on. For each μ-CHP product, a specific constant mass flow rate of the pump is selected to keep the temperature difference (T_3-T_2 in Figure 8) at 10 °C. In this way, the supply temperature from the μ-CHP (T_3) never exceeds 65 °C. The heat transfer fluid of DHW, AHU, and space heating all flow through the (HWST) before passing to the auxiliary electrical heaters. The auxiliary electrical heaters are turned on when the set point temperatures of the heat transfer fluid are not met by the HWST. Meanwhile, in original publication II, the generated electrical power (G_{elec}) from the μ-CHP is compared to electrical demands, which include the electrical demands of the devices and appliances of the single-family house, the auxiliary electrical heaters, and the circulating pumps. If G_{elec} is higher than the electrical demands, it will be exported to the electrical grid. On the other hand, if G_{elec} is not enough to cover the electrical demands, the electrical power will be imported from the electrical grid. The investigation of installing electrical storage under thermal tracking strategy is carried out in original publication II. In original publication III, the PV modules as an on-site supplementary system are installed to fulfil the NZEB balance when the balance is not fulfilled by the μ-CHP alone. The hourly total generated electricity ($G_{tot,el}$) summing of the electricity generated by the μ-CHP ($G_{CHP,el}$) and the PV modules ($G_{PV,el}$) is compared to the hourly electric demands (L_{el}), which includes appliances, lighting, HVAC equipment, circulated pumps, and auxiliary electrical heaters demands. If the $G_{tot,el}$ is higher than the L_{el}, the surplus electrical power will be exported. If the $G_{tot,el}$ is lower than the L_{el}, the shortage will be compensated by electricity imported from the electrical grid. As long as original publication III focuses on NZEB with availability to import the shortage of the electrical demand and export the surplus generated electricity to and from the electrical grid, adding electrical storage is not analyzed under the thermal tracking strategy. It should be noted that the building is not connected with a thermal grid in case the μ-CHP operates under the thermal tracking strategy. This means that the μ-CHP thermal capacity and the auxiliary heaters should be able to cover all thermal loads.

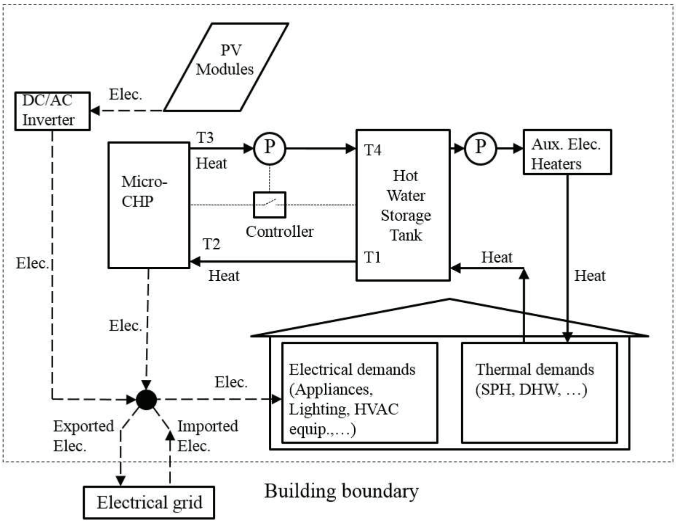

Figure 8 The control principle of the thermal tracking strategy, thermal connections of the μ-CHP, and electric connections of the μ-CHP and the PV modules. (Original publication III)

Figure 9 presents a brief schematic of the control principle for the electrical tracking strategy. In contrast to the thermal tracking strategy, the μ-CHP and the pump are controlled by the fractional state of charge (FSOC) of the battery (an indicator describes how much the battery capacity is in respect to its full capacity) instead of the bottom tank temperature. If the FSOC of the battery is higher than 0.95, both the μ-CHP and pump will be turned off, whereas if the FSOC is lower than 0.3, both the μ-CHP and the pump will be turned on. The reason why the start-up FSOC for the μ-CHP is chosen to be 0.3 instead of 0.2 is to reduce the chances for a situation in which the battery is at the deepest FSOC of 0.2, when electricity has to be imported from the electrical grid to cover the shortage. Furthermore, with the electrical tracking strategy, there is no electricity being exported to the electrical grid. Meanwhile, the μ-CHP is connected to the HWST. Same as under thermal tracking strategy, for each μ-CHP product, a specific constant mass flow rate of the pump is selected to keep the temperature difference (T_3-T_2 in Figure 9) at 10 °C. Under the electrical tracking strategy, the μ-CHP and pump might be still in operation even if the bottom tank temperature (T_1 in Figure 9) is higher than 55 °C. If this situation happens (T_1>55 °C), it is assumed that the heat transfer fluid will flow through a heat exchanger to export the heat to the heat grid, and the return temperature (T_2) back to the μ-CHP after this exporting process is assumed to be at 55 °C. In this way, the supply temperature from the μ-CHP (T_3) never exceeds 65 °C. By knowing the mass flow rate and the temperature difference of T_1 and T_2, the amount of heat power exported can be calculated. The exportation of heat at this medium temperature level (55-65 °C) often occurs using the technology of “Feed-in return → return”, which is one of the heat grid feed-in technologies where heat is exchanged from the heat exchanger to the thermal grid through the return mainline of the thermal grid as defined in [66]. Since the thermal heat grid is available in the electrical tracking strategy, the auxiliary heating device is by the thermal heat grid instead of the electrical heater. In original publication III, the STC modules as an on-site supplementary system are installed to fulfil the NZEB balance when the balance is not fulfilled by the μ-CHP alone. It should be noted that the electrical consumption of the circulating pump of STC system is added to the electrical demand.

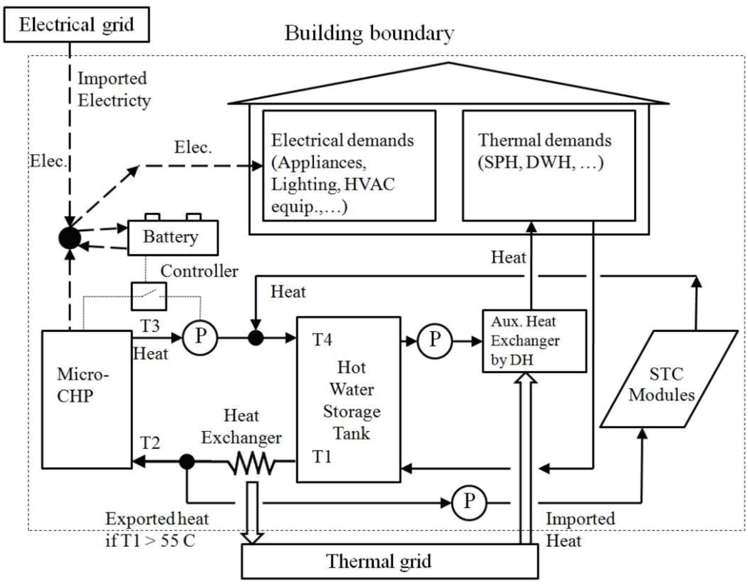

Figure 9 The control principle of the electrical tracking strategy, electrical connections of the μ-CHP, and thermal connections of the μ-CHP and the STC modules. (Original publication III)

It should be mentioned that optimizing the HWST and electrical battery sizes are out of the aim of this study. Therefore, they are chosen to be with reasonable sizes with the single family house application as it will be presented in the case study. For all of the simulated cases, the HWST size is 0.3 m^3. When a battery exists in the system, the battery size is chosen as 100 Ah (48 V). Meanwhile, the comparison of different μ-CHP systems' characteristics using parametric analyses will be fair when the HWST and battery sizes are kept constant.

3.6 Different weighting factors' scenarios (original publication II)

Original publication II included a review of the commercial μ-CHP products within range less than 3 kWe. It is found that the most common nominal electrical output power (Gelec) is 1 kWe, while the power-to-heat ratio (means the ratio between the nominal electrical and thermal power of the CHP) (P/H) is mainly in the range of 0.05-0.6. Therefore, in the latter parametric analysis, we designate Gelec(t) at 1kWe, and the studied range of P/H from 0.05 to 0.8 with an P/H step of 0.05. However, three other μ-CHP electrical capacities are investigated in original publication II. The implementation of the WMI is conducted by focusing on the parameters of the μ-CHP products which are only limited to the power to heat ratio (P/H ratio). Furthermore, the influence of the weighting factor on the WMI value is conducted with four scenarios presented in Table 9. The selected examples reflect real cases in practice as follow. Scenario A can happen in a situation where the house owner pays more attention to electrical matching than heat matching, for example because the electrical grid tariff is much more expensive than the district heating tariff; Scenario B can happen in a situation where the house owner pays more attention to heat matching than electrical matching, for example because the district heating tariff is much more expensive than the electrical grid tariff; Scenario C can happen in a situation where the house owner tries to meet the low-energy or zero-energy balance of the house, or in a situation where the feed-in tariff to the (electrical and heat) grid is much more expensive than the import tariff; Scenario D can happen in a situation where the feed-in tariff to the (electrical and heat) grid is zero or much less than the import tariff and the house owner tries to utilize the on-site generation for local demand to the largest extent. In addition to the four examples, under a special situation when the weighting factors of all the detailed energy matching indices are equal i.e. w_i = 0.25 according to Eq. (18), the WMI is defined as the "average mating index = AMI".

Table 9 Four scenarios of the weighting factors. (Original publication II)

Scenarios	Underlying Principle	w_1 (a)	w_2 (a)	w_3 (a)	w_4 (a)
A	Electrical matching is more important than thermal heat matching	0.375	0.375	0.125	0.125
B	Thermal heat matching is more important than electrical matching	0.125	0.125	0.375	0.375
C	Covering local demand by on-site generation is more important than utilizing on-site generation by local demand	0.375	0.125	0.375	0.125
D	Utilizing on-site generation by local demand is more important than covering local demand by on-site generation	0.125	0.375	0.125	0.375

(a) According to Equation (18), w_1, $w2$, $w3$ and w_4 are the weighting factors for OEFe, OEMe, OEFh, and OEMh, respectively.

3.6.1 Parametric analysis of WMI for the thermal tracking strategy

Figure 10 presents the simulation results of the annual WMI values of the four scenarios in respect to certain P/H while Figure 11 presents the simulation results of the annual extended indices' values in respect to certain P/H under the thermal tracking strategy. Also the AMI curves are illustrated in both figures for comparison purposes. According to the assumptions listed in Table 9, the WMI_A curve is more influenced by the evolutions of OEFe and OEMe than those of OEFh and OEMh, whereas the situation is the reverse with the WMI_B curve. According to the control principle for the thermal tracking strategy, the overall matching situation of the thermal heat aspect is generally better than that of the electrical aspect. Furthermore, with the thermal tracking strategy, the OEMh is always kept at 1.00. Moreover, as shown in Figure 11, the OEMe and OEFh curves are always kept at a high level, above 0.6, while the OEFe curve fluctuates in respect to the P/H and always lies below the other detailed matching index curves. The WMI_C curve is always kept at a lower level than the AMI curve and is significantly affected by the fluctuation in the OEFe as long as more preference is put on the OEF than on the OEM as given in Table 9. The WMI_B and WMI_D curves can be explained with a similar manner i.e. the influence of the preferences of the detailed matching indices and the behavior of the detailed matching indices themselves. The effect of installing the battery with the thermal tracking operation strategy on the annual detailed matching indices are investigated and discussed in original publication II.

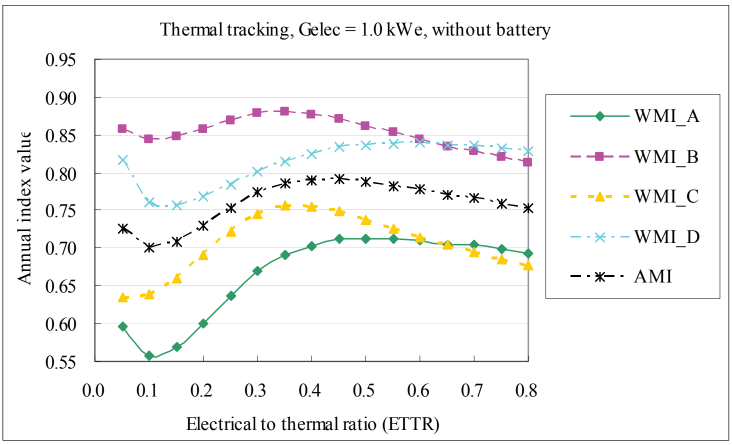

Figure 10 The impact of the weighting factor on the WMI values under the condition of thermal tracking without battery, with G_{elec} of 1.0 kWe. Electrical to thermal ratio (ETTR) is referred to by P/H in the text. (Original publication II)

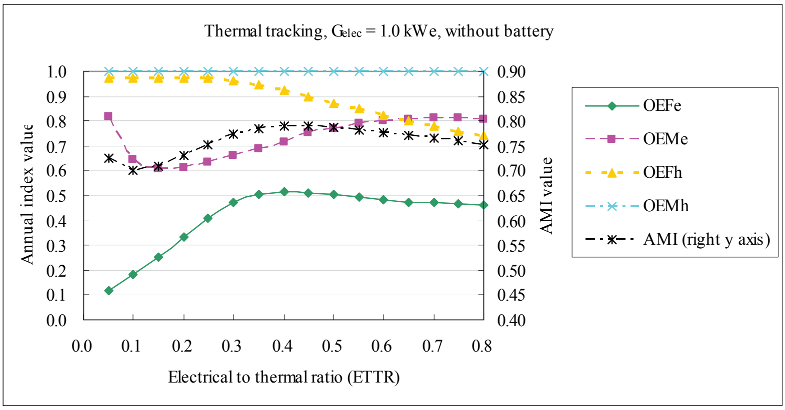

Figure 11 The detailed four matching indices and AMI for thermal tracking without battery under G_{elec} of 1.0 kWe. Electrical to thermal ratio (ETTR) is referred to by P/H in the text. (Original publication II)

3.6.2 Parametric analysis of the WMI for the electrical tracking strategy

Figure 12 presents the simulation results of the annual WMI values of the μ-CHP in respect to the P/H under the electrical tracking strategy, while Figure 13 presents the simulation results of the annual extended indices' values of the μ-CHP under the electrical tracking strategy. In addition, the AMI curves are illustrated in both figures for comparison purposes. Due to the electrical tracking strategy, electrical matching is better than thermal heat matching, leading to the fact that the WMI_A curve is above the AMI curve whereas the WMI_B curve is below the AMI curve. The WMI_A and WMI_C curves have similar profiles at the P/H range of 0.05 and 0.2. However, as the P/H increases from 0.2, the WMI_C curve continuously decreases whereas WMI_A is relatively stable. This can be explained as follows. Under the electrical tracking strategy, with the increase of P/H, the thermal heat power ($G_{h\_th}(t)$) generated by the μ-CHP continuously decreases, and heating demand is more dependent on the auxiliary heating device, i.e. the heating grid. Therefore, as P/H increases from 0.05 to 0.80, the OEMh continuously increases, while the OEFh continuously decreases. Meanwhile, OEFe and OEMe both stabilize above 0.9, as shown in Figure 13. Considering the weighting factors of scenario A and C listed in Table 9, the difference between the WMI_A and WMI_C curves is more sensitive to the fluctuation of OEFh than to other extended indices. With a higher w_3 (0.375) in scenario C than that (0.125) in scenario A, the WMI_C curve significantly decreases when the P/H increases from 0.2 to 0.8. The difference between the WMI_B and WMI_D curves can be explained in a similar manner. The main findings from the parametric analysis of the WMI for thermal and electrical tracking strategies is that the best matching case is affected by the weighting factors selection of the WMI regarding the which scenario is important to the designer.

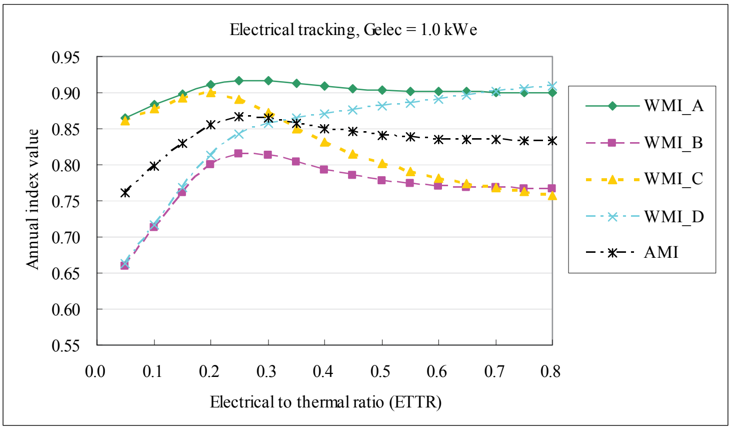

Figure 12 The impact of the weighting factors on the WMI values under the condition of electrical tracking with G_{elec} of 1.0 kWe. Electrical to thermal ratio (ETTR) is referred to by P/H in the text. (Original publication II)

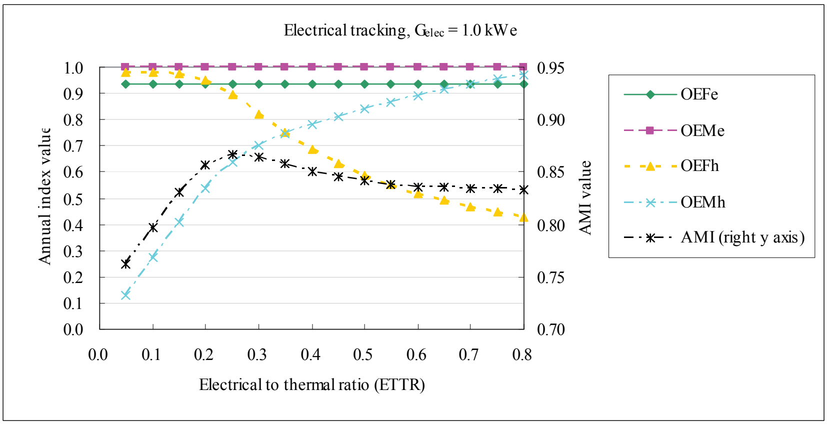

Figure 13 The detailed four matching indices and AMI for the electrical tracking strategy under G_{elec} of 1.0 kWe. Electrical to thermal ratio (ETTR) is referred to by P/H in the text. (Original publication II)

3.7 Comparison between matching and net primary energy consumption

In this section, the comparison between the annual net primary energy consumption (ANPE) and the annual matching capability are investigated. It is assumed that the μ-CHP is fed by substitute natural gas from biomass (bio-syngas). The NRPE factors for grid electricity, district heating, and bio-syngas are given in Table 8. The building boundary is the footprint area of the standard house. The exported energy is multiplied by the same NRPE factor as the imported one based on the concept of displaced non-renewable energy in the electrical or thermal heat grid. Still using the same electrical output level G_{elec} of 1.0 kWe as the common available commercial μ-CHP units. The overall efficiency for the μ-CHP is assumed to be at 0.9 for all the cases.

Figure 14 presents the results of ANPE for the two selected groups of cases; under thermal and electrical tracking strategies. An ANPE equal to or below zero indicates that the house is a “net-zero energy building” (ANPE = 0) or a “plus-energy building” (ANPE < 0) over the year. As shown in Figure 14, under the thermal tracking strategy without a battery for G_{elec} of 1.0 kWe, when the P/H increases from 0.05 to 0.8, more electricity is generated by the μ-CHP. However, the increase in electrical generation does not lead to a constantly increasing amount of electrical export to the electrical grid because a higher P/H results in greater dependency on the auxiliary electrical heaters, and thus, increased electrical demands. Therefore, the ANPE profile does not constantly decrease in respect to the increase of P/H, but presents a profile as shown in Figure 14. On the other hand, under the electrical tracking strategy for G_{elec} of 1.0 kWe, the relationships between the AMI and ANPE are not directly relevant to one another. Better matching does not necessarily mean a lower ANPE. The P/H value of 0.05 refers to the worst matching (the lowest AMI of 0.76) and the lowest ANPE (-342 kWh/m^2 a). The reason for this is that under the electrical tracking strategy, when the P/H is at a low level (e.g. at 0.05), the export of thermal heat to the heat grid is quite significant (700.8 kWh/m^2 a, which is seven times higher than the heating demands). As a result, the OEMh is extremely low (lower than 0.13 at the P/H of 0.05), and the overall AMI is at the lowest value of 0.76. However, this high level of thermal heat grid export is beneficial for reducing the ANPE. It can be concluded that there is no linear relation between annual matching capability and annual net primary energy consumption. The annual energy matching analysis can provide an idea about the early design needs of the NZEB case therefore it is considered relevant.

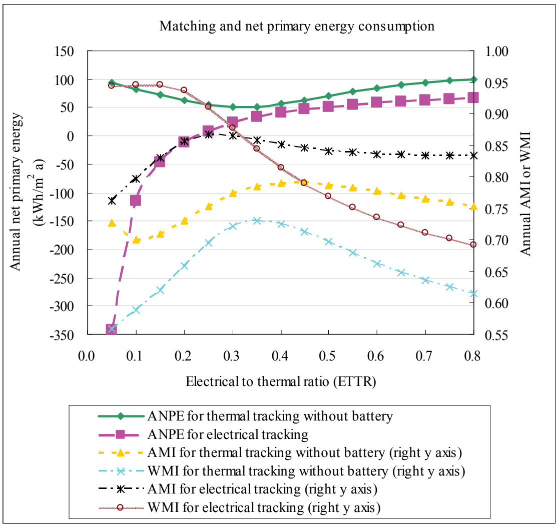

Figure 14 Matching and net primary energy consumption for G_{elec} of 1.0 kWe. (Original publication II)

3.8 Weighting factors of the WMI and their mathematical models (original publication III)

The weighting factors in the WMI definition are preferences, reflecting the importance of each extended matching index from the matching analysis point of view. To assess building-grid interaction, especially for nearly and net ZEB, two extreme situations have to be quantified using the suitable indicator(s) as given in [10]. The two opposite extreme situations are (i) a load-matching priority strategy (maximizing the load matching), (ii) an energy export priority strategy (maximizing the energy export). These two opposite extreme situations will be defined by NZEB matching situations. The load-matching priority strategy means that the self-consumption of the on-site generated energy has to be maximized. This means maximizing (w_1 OEFe + w_3 OEFh) in Eq. (18). The energy export priority strategy means that the on-site generated energy has to be exported regardless of the building's load or storage possibilities, aiming to fulfill the balance with the imported energy. This means minimizing (w_2 OEMe + w_4 OEMh) in Eq. (18).

The matching analysis is conducted in respect to the boundary B2. In the case of analyzing the μ-CHP without any PV or STC modules, let's first allocate the NRPE factor of the fuel supply of the μ-CHP to the generated electricity $G_{CHP,el}$ and heat $G_{CHP,h}$. The used allocation method is the “energy content of the product” [67]. The input primary energy associated with the input fuel is allocated based on the energy content of the electricity and heat production. In this study, the energy content refers to the lower heating value (LHV) of the fuel supply. The NRPE factors of the generated electricity $f_{CHP,e}$ and heat $f_{CHP,h}$ can be obtained as shown by Eqs. (19) and (20).

$$f_{CHP,el} = \frac{X_e * f_F * Q_F}{G_{CHP,el}} = \frac{\eta_{CHP,el}}{\eta_{CHP,overall}} * f_F * \frac{1}{\eta_{CHP,el}} = \frac{f_F}{\eta_{CHP,overall}} \tag{19}$$

$$f_{CHP,h} = \frac{X_h * f_F * Q_F}{G_{CHP,h}} = \frac{\eta_{CHP,h}}{\eta_{CHP,overall}} * f_F * \frac{1}{\eta_{CHP,h}} = \frac{f_F}{\eta_{CHP,overall}} \tag{20}$$

X_e and X_h are the proportions of the associated NRPE with the generated electricity and heat, respectively. Q_F is the amount of the energy content of the fuel fed to the μ-CHP. The electric, thermal, and overall efficiencies of the μ-CHP are $\eta_{CHP,el}$, $\eta_{CHP,h}$, $\eta_{CHP,overall}$, respectively.

Eqs. (21) - (22) show how X_e and X_h are calculated based on the energy content allocation method.

$$X_e = \frac{G_{CHP,el}}{G_{CHP,h} + G_{CHP,el}} = \frac{G_{CHP,el}}{\eta_{CHP,overall} * Q_F} = \frac{\eta_{CHP,el}}{\eta_{CHP,overall}} \tag{21}$$

$$X_h = \frac{G_{CHP,h}}{G_{CHP,h} + G_{CHP,el}} = \frac{G_{CHP,h}}{\eta_{CHP,overall} * Q_F} = \frac{\eta_{CHP,h}}{\eta_{CHP,overall}} \tag{22}$$

3.8.1 Weighting factors of the WMI for μ-CHP

By taking a look at the crediting factors of different energies such as the NRPE factors, CO_2 equivalent emission factors, or costs, it is found that in most cases, grid electricity has the highest factors, then fossil fuels, then district heating, then renewable energies whether it is renewable fuel (i.e. biogas or biomass) or solar energy. Thus, the NRPE factors, CO_2 equivalent emission factors, and the costs of the fuel supply and the imported and exported energies from/to the grids can be used to calculate the weighting factors of the WMI. The physical and mathematical explanation is described as follows. The weighting factor (w_1) of the on-site electrical energy fraction OEFe is calculated based on the grid electricity NRPE factor, because the OEFe identifies the proportion of energy demand covered by the on-site electrical energy generation instead of the grid electricity. Similarly, the on-site generated heat replaces the thermal heating grid to cover the thermal demand, partially or totally, based on the control strategy and the characteristics of the μ-CHP. Therefore, the weighting factor (w_3) of the on-site thermal energy fraction OEFh can be correspondingly calculated based on the thermal heat grid NRPE factor. The OEM identifies the on-site generated energy proportion being consumed in the building and the system rather than being exported or dumped. Therefore, the weighting factors (w_2) and (w_4) of OEMe and OEMh can be reasonably calculated to reflect the NRPE factors of the on-site electrical and thermal energy generated by the μ-CHP, respectively. The (w_2) and

(w_4) always have the same values due to the use of the simple energy content allocation method.

Mathematically, each weighting factor w_i is expressed as a ratio of its corresponding NRPE factor f_i as physically illustrated by the sum of all NRPE factors of energies crossing the boundary B2 shown in Figure 7, as given by Eq. (23).

$$w_i = \frac{f_i}{\sum_j f_j} \tag{23}$$

The weighting factor of OEFe, i.e. w_1, is calculated in respect to the proportion of the NRPE factor of grid electricity $f_{el,grid}$ in respect to the sum of the four NRPE factors $f_{grid,el}$, $f_{grid,h}$, $f_{CHP,e}$, $f_{CHP,h}$. The weighting factor of OEFh, i.e. w_3, is similarly calculated as a ratio of $f_{grid,h}$ to the sum of the four NRPE factors. The weighting factors of OEMe and OEMh, i.e w_2 and w_4, respectively, are calculated as a ratio of $f_{CHP,e}$ and $f_{CHP,h}$ to the sum of the four NRPE factors, respectively. The mathematical formulas of calculating the weighting factors are given by Eq. (24).

$$w_1 = \frac{f_{grid,el}}{f_{grid,el} + f_{grid,h} + f_{CHP,el} + f_{CHP,h}} \tag{24.a}$$
$$w_2 = \frac{f_{CHP,el}}{f_{grid,el} + f_{grid.h} + f_{CHP,el} + f_{CHP,h}} \tag{24.b}$$
$$w_3 = \frac{f_{grid,h}}{f_{grid,el} + f_{grid,h} + f_{CHP,el} + f_{CHP,h}} \tag{24.c}$$
$$w_4 = \frac{f_{CHP,h}}{f_{grid,el} + f_{grid,h} + f_{CHP,el} + f_{CHP,h}} \tag{24.d}$$

Table 10 shows the weighting factors w_i of the WMI for the μ-CHP fed by NG and bio-syngas with 90% $\eta_{CHP,overall}$ when the NRPE factors in Table 8 are used.

Table 10 The weighting factors of the WMI for μ-CHP fed by bio-syngas and natural gas (NG). (Original publication III)

Fuel supply of μ-CHP	w_1 of OEFe	w_2 of OEMe	w_3 of OEFh	w_4 of OEMh
Bio-syngas	0.660	0.056	0.228	0.056
Natural gas	0.403	0.229	0.139	0.229

As a result of the high NRPE factor of grid electricity (or other crediting factors like CO_2 emission factors or costs, due to the fact that electricity has the highest energy quality), w_1 will always be the highest among the weighting factors as shown in Table 10. This reflects the NZEB matching situations from the electrical matching analysis (i.e. high w_1 and low w_2) regardless of the fuel source of the μ-CHP. It also reflects the energy quality by putting more preference on electricity than thermal energy (i.e. w_1 is higher than w_3). From the thermal heat matching analysis (i.e. comparing between values w_3 and w_4), two opposite results are obtained regarding the fuel source of the μ-CHP as shown in Table 10. For bio-syngas, w_3 is higher than w_4, reflecting the NZEB matching situations, while w_4 is higher than w_3 for NG as an opposite result. For NG, the results indicate that it does not make sense to import NG with an NRPE factor of 1.14 and generate on-site thermal energy from the μ-CHP with an NRPE factor of 1.27 (which is equal to 1.14 divided by $\eta_{CHP,overall}$ of 0.9) to export to and/or replace the thermal heating grid from DH, which already has an NRPE factor of 0.77. It can be concluded that calculating the weighting factors based on the NRPE factors (or any other crediting factors like the CO_2 emission factor or cost) defines situations either in-line with or reverse to NZEB matching situations, taking into account the energy quality and energy conversion as well.

3.8.2 Weighting factors of the WMI for hybrid on-site generation systems

The suggested methodology for calculating weighting factors is based on the NRPF of the fuel used by the on-site generation system. With hybrid on-site generation systems, i.e. μ-CHP with PV and/or STC modules, there should be a single value for the NRPE factor which can be used to calculate the weighting factors. Therefore, the on-site overall NRPE factors $f_{on\text{-}site,overall,el}$ and $f_{on\text{-}site,overall,h}$ are suggested for the on-site generation of electricity and heat, respectively. The overall NRPE factor is calculated proportionally for each of the electrical and thermal generated energies via all on-site supply systems as shown in Eq. (25). For example, as shown in Figure 7, electricity and heat are produced on-site by the μ-CHP and the PV module, and the μ-CHP and the PV module, respectively. Therefore, the overall on-site electricity and heat generated NRPE factors can be calculated as shown in Eq. (26).

$$f_{on-site,overall,el} = \frac{\sum_{i=1}^{n}(f_{i,el} * G_{i,el})}{\sum_{i=1}^{n} G_{i,el}} \tag{25.a}$$

$$f_{on-site,overall,h} = \frac{\sum_{i=1}^{n}(f_{i,h} * G_{i,h})}{\sum_{i=1}^{n} G_{i,h}} \tag{25.b}$$

$$f_{on-site,overall,el} = \frac{(f_{CHP,el} * G_{CHP,el} + f_{solar,el} * G_{PV,el})}{G_{CHP,el} + G_{PV,el}} \tag{26.a}$$

$$f_{on-site,overall,h} = \frac{(f_{CHP,h} * G_{CHP,h} + f_{solar,h} * G_{STC,h})}{G_{CHP,h} + G_{STC,h}} \tag{26.b}$$

The weighting factors of the WMI are then calculated using Eq. (27) as follows

$$w_1 = \frac{f_{grid,el}}{f_{grid,el} + f_{grid,h} + f_{on-site,overall,el} + f_{on-site,overall,h}} \quad (27.a)$$

$$w_2 = \frac{f_{on-site,overall,el}}{f_{grid,el} + f_{grid,h} + f_{on-site,overall,el} + f_{on-site,overall,h}} \quad (27.b)$$

$$w_3 = \frac{f_{grid,h}}{f_{grid,el} + f_{grid,h} + f_{on-site,overall,el} + f_{on-site,overall,h}} \quad (27.c)$$

$$w_4 = \frac{f_{on-site,overall,h}}{f_{grid,el} + f_{grid,h} + f_{on-site,overall,el} + f_{on-site,overall,h}} \quad (27.d)$$

The weighting factors w_i will change from case to case when this method is applied for μ-CHP with PV and/or STC modules. However the NRPE factor of solar energy is considered equal to zero as referring to the portion of non-renewable energy consumed to produce electricity or thermal energy from the PV and STC (Table 8), the PV and STC modules as supplementary systems varies from case to case fulfilling the annual NZEB balance with the μ-CHP as the main on-site energy supply system.

3.9 The WMI with weighting factors calculated by proposed model

3.9.1 Parametric analysis of on-site μ-CHP under the thermal tracking strategy

The extended matching indices calculation depends only on the electrical and thermal energies as shown by Eqs. (12) - (19); thus, they have the same values for both bio-syngas- and NG-fueled μ-CHPs. The weighting factors of the extended matching indices are shown in Table 10. The WMIs of the bio-syngas- and NG-fueled μ-CHPs as the on-site energy systems are shown in Figure 15-a and -b, respectively, where the variation between the bio-syngas and NG μ-CHPs is only due to a variation of the weighting factors. In Figure 15-a, the highest WMI is 0.75, corresponding to 2.0 kWe bio-syngas-fueled μ-CHP and 0.8 P/H ratios. Moreover, for the cases fulfilling the NZEB balance, the bio-syngas-fueled μ-CHP with a nominal capacity of 2.0 kWe and P/H ratio range of 0.6 to 0.8, has a high range of WMI of 0.69 to 0.75. It can be observed that, for the bio-syngas-fueled μ-CHP of 0.5 kWe and 1.0 kWe electrical capacities, the P/H ratios are 0.15 and 0.35 for the highest WMI values, respectively. For the NG-fueled μ-CHPs in Figure 15-b, the highest WMI is 0.77, corresponding to 1.5 kWe μ-CHP and 0.8 P/H ratios. When the ratio of w_1/w_3 is large, as in the bio-syngas-fueled μ-CHP, the highest WMI is obtained by the μ-CHP which has a minimum nominal electrical capacity, achieving the NZEB balance as shown by 2.0 kWe. On the contrary, when the ratio of w_1/w_3 is small, as in the NG-fueled μ-CHP, the highest WMI is obtained by the μ-CHP, which reaches the minimum net primary energy consumption and starts to rise again within the range of the P/H ratio. It can also be noticed that the peak WMI shifts toward higher P/H ratio in both Bio-syngas- and NG- fueled μ-CHP as the nominal electrical capacity increases. This is due to increasing the OEFe, which has the highest weighting factor *w1* of 0.66.

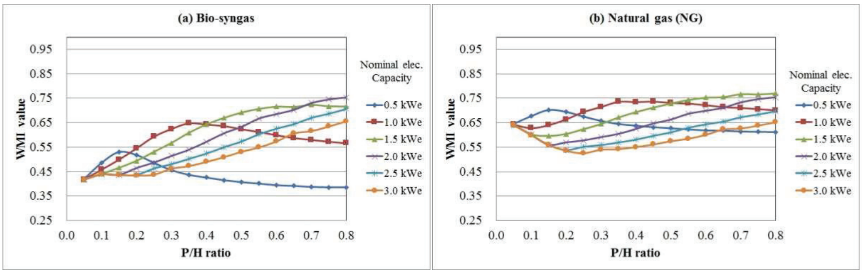

Figure 15 The overall annual weighting matching index WMI for μ-CHPs under the thermal tracking strategy. (Original publication III)

Figure 16 shows the imported and exported primary energy of bio-syngas- and NG-fueled μ-CHPs under the thermal tracking strategy. This figure was suggested to present an overall view of the matching situation [68], but without detailed quantitative values as given by the WMI and the extended matching indices, taking into account all energy imported and exported carriers, including the fuel supply (i.e. energies crossing the boundary B1). Each analyzed case is presented by a single point, which has imported and exported primary energy values on the X and Y axes. Any point that lies on or above the zero energy balance line fulfills the NZEB balance between imported and exported primary energies. The lowest imported primary energy represents the best matching situation regarding the covering demand by on-site generated energies. The lowest exported primary energy represents the best matching situation regarding on-site generation utilized by building demands. For the bio-syngas-fueled μ-CHP in Figure 16-a, the case of 2.0 kWe bio-syngas-fueled μ-CHP and 0.8 P/H ratios, which has the minimum imported primary energy fulfilling the NZEB balance, is the same as that has been obtained by the WMI. For the NG-fueled μ-CHP in Figure 16-b, the import/export primary energy figure does not refer to the same conclusions as the WMI. The reason is that the extended matching indices deal with electrical and thermal energies, not like the import/export primary energy balance, which does not distinguish between the different energy carriers including the fuel supply. Accordingly, the NRPE factors (i.e. associated imported primary energies) of both bio-syngas and NG fuels are the main reason to change the obtained results by the import/export figures.

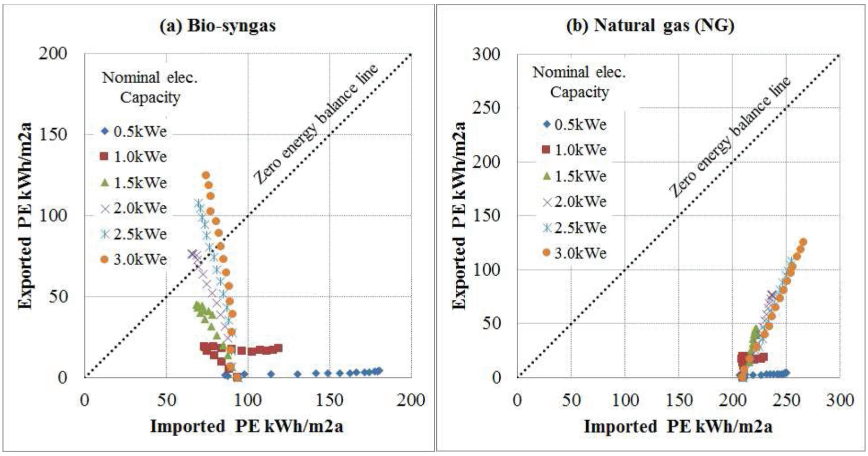

Figure 16 Imported and exported primary energy of μ-CHPs under the thermal tracking strategy. (Original publication III)

3.9.2 Parametric analysis of on-site μ-CHP and PV under thermal tracking strategy

The WMI for all cases fulfilling the NZEB balance are shown in Figure 17. It should be noted that the weighting factors used to calculate the WMI vary from case to case depending on the PV area and methodology as illustrated in section 3.8.2. For instance, the variations of w_1, w_3, and w_4 are between +5% and 0%, while the variation of w_2 is between 0% and -89%. The main reason is related to the zero NRPE factor of solar energy. For the bio-syngas-fueled μ-CHP in Figure 17-a, the highest WMI has a value of 0.775, corresponding to1.5 kWe μ-CHP at P/H ratio of 0.7 and a PV area of 23 m². The reason for changing the highest matching case from 2.0 kWe μ-CHP without installing any PV (Figure 15-a) to 1.5 kWe μ-CHP with a 23 m² PV area is that the OEFe, which has higher weighting factors w_1, is enhanced due to the fact that 42% of the produced electricity from the PV modules is utilized by electricity needs. For the NG-fueled μ-CHP in Figure 17-b, the highest WMI has a value of 0.775, corresponding to 2.0 kWe μ-CHP at a P/H ratio of 0.8 and a PV area of 116 m². The fluctuations of the WMI values in Figure 17 are related to the fluctuations of the OEFe and OEMe, which are affected by coupling the PV system (especially for 3.0 kWe μ-CHP, which has the lowest operating hours and highest on/off cycling compared to others at each P/H ratio).

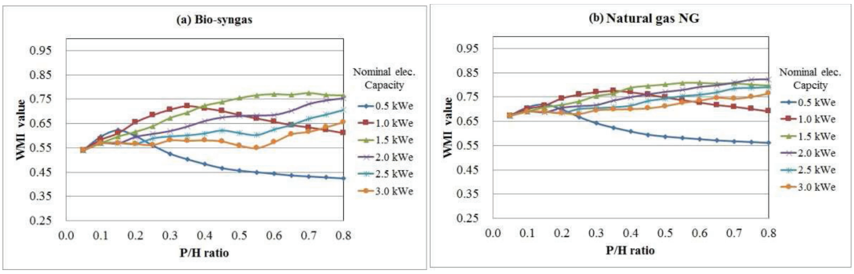

Figure 17 The overall annual weighting matching index for μ-CHP and PV modules under the thermal tracking strategy. (Original publication III)

3.9.3 Parametric analysis of on-site μ-CHP under the electrical tracking strategy

The WMI of the μ-CHP under the electrical tracking strategy is shown in Figure 18. Since the WMI of μ-CHPs over 1.0 kWe electrical capacity are quite similar (the 1.5 and 2.0 kWe μ-CHP have a WMI slightly higher than the 1.0 μ-CHP) as shown in Figure 18-a and -b, the 1.0 kWe bio-syngas-fueled μ-CHP is selected to represent the highest WMI of 0.92 with a P/H ratio of 0.2, and the 1.0 kWe NG-fueled μ-CHP represents the highest WMI of 0.89 with a P/H ratio of 0.8. It can be noticed that the WMI values of the electrical tracking strategy are higher than that of the thermal tracking strategy, because the OEFe has the highest weighting factor equal to 0.73 for the μ-CHP of 0.5 kWe and 0.94 for the μ-CHP of electrical capacity which is equal to or more than 1.0 kWe. Regarding the NG-fueled μ-CHP, as shown in Figure 18-b, the OEMh weighting factor w_4 of 0.229, as given in Table 10, is higher than the OEFh weighting factor w_3 of 0.139, reflecting reverse NZEB matching situations by giving priority to utilizing on-site generated thermal energy over covering local demand by on-site generated thermal energy. The WMI is approximately constant for all NG-fueled μ-CHP which have a P/H ratio higher than 0.2 because of the fact that multiplying the OEFh and OEMh by a w_3 of 0.229 and a w_4 of 0.139, respectively, neglects the influence of decreasing OEFh (e.g. for 1.0 kWe μ-CHP, OEFh decreases from 0.95 at a 0.2 P/H ratio to 0.44 at a 0.8 P/H ratio) and increasing OEMh (e.g. for 1.0 kWe μ-CHP, OEFh increases from 0.54 at a 0.2 P/H ratio to 0.97 at a 0.8 P/H ratio) with increasing the P/H ratio.

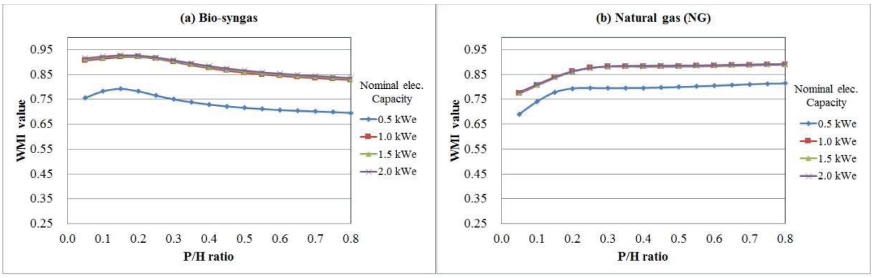

Figure 18 The overall annual weighting matching index for μ-CHPs under the electrical tracking strategy. (Original publication III)

The imported and exported primary energy for the μ-CHPs under the electrical tracking strategy are shown in Figure 19. As shown in Figure 19, for both bio-syngas- and NG-fueled μ-CHPs, the import/export primary energy figures indicate approximately the same highest matching cases as given by the WMI. The reason for obtaining the same results by the WMI and the import/export figures for bio-syngas-fueled μ-CHPs is the very low NRPE factor of bio-syngas fuel. While for NG-fueled μ-CHPs, the reasons are related to the high NG NRPE factor and the control strategy used. Because of this, the NG fuel NPEF factor is higher than the thermal heat grid NRPE factor; the increasing P/H ratio of the μ-CHPs reduces the total imported primary energy, and the required exported thermal heat fulfilling the NZEB as given in Figure 19-b.

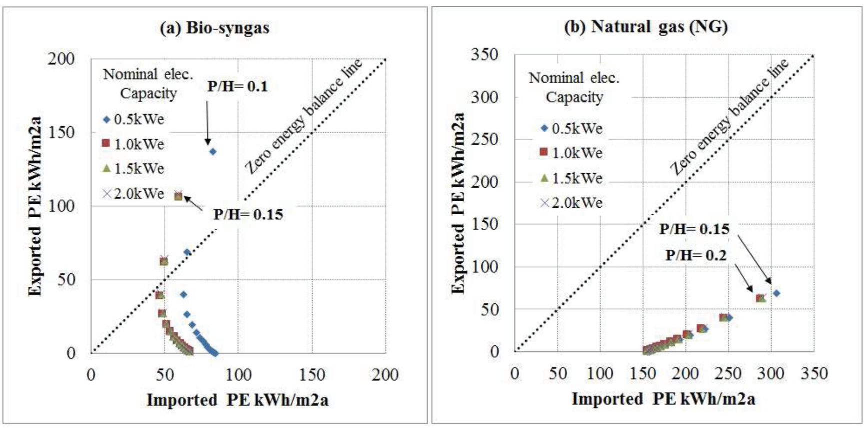

Figure 19 Imported and exported primary energy of μ-CHPs under the electrical tracking strategy. (Original publication III)

3.9.4 Parametric analysis of on-site μ-CHP and STC under electrical tracking strategy

Figure 20 shows the WMI for all cases after fulfilling the NZEB under the electrical tracking strategy. For the bio-syngas-fueled μ-CHP in Figure 20-a, it can be observed that the 1.0 kWe μ-CHP with a P/H ratio of 0.2 still has the highest WMI. Also, for all cases with STC, the WMI is slightly decreased (with 0.03 for 0.5 kWe μ-CHP and 0.01 for others) compared to cases without STC. The reason is that OEMh is decreased by increasing the exported thermal energy due to installing the STC modules. For the NG-fueled μ-CHP in Figure 20-b, the relations between the weighting factors come in line with the NZEB matching situations, i.e. $w_1 > w_2$, and $w_3 > w_4$. The weighting factors w_1, w_2, w_3, and w_4 vary between (0.454 - 0.502), (0.258 - 0.285), (0.157- 0.173), and (0.123 - 0.040), respectively. Therefore, the 1.0 kWe μ-CHP with a P/H ratio of 0.2 with 82 STC modules has the highest WMI of 0.88. The characteristics of μ-CHP with STC modules varied from the μ-CHP alone due to the OEMh. The OEMh increases from 0.05 to 0.18 within range of the P/H ratio of 0.05 to 0.2 multiplied by relatively high w_4 ($0.13 > w_4 > 0.1$) getting the highest WMI, then it becomes constant with va alue of 0.2 within the P/H ratio range of 0.25 to 0.8 multiplied by relatively low w_4 ($0.1 > w_4 > 0.05$) reducing the WMI slightly within the P/H ratio range of 0.25 to 0.8.

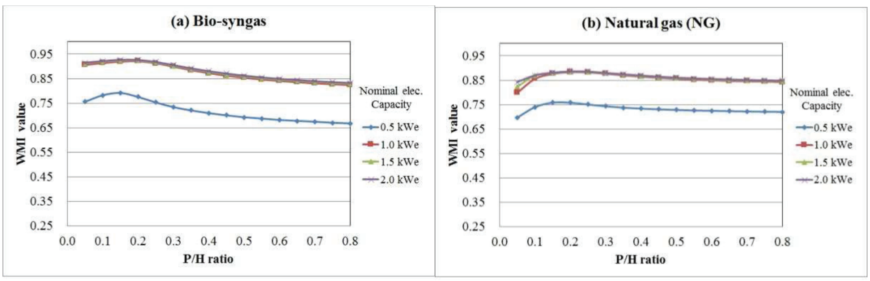

Figure 20 The overall annual weighting matching index for μ-CHP and STC modules under the electrical tracking strategy. (Original publication III)

3.10 Summary

Section 3 can be summarized as follows. The energy matching topology introduced earlier in Section 1.3.2 was developed to be able to handle the energy matching analysis of the micro-cogeneration system operated under thermal tracking with a electrical grid feed-in scheme and electrical tracking with a thermal heat grid feed-in scheme. The most important contribution is developing an overall matching index WMI by combining the extended indices by multiplying them by certain weighting factors expressing the preferences of each. Both the overall and extended indices can be used to analyze the matching situation from both the overall viewpoint and as well as detailed specific viewpoints. The weighting factors calculation model of the WMI proposes physically and mathematically based non-renewable primary energy (NRPE) factors (or other such as CO_2 equivalent emission factors and costs) for the different energy carriers crossing the building boundary. Besides that the proposed model aims basically to be applied on the micro-cogeneration (μ-CHP) under thermal and electrical tracking strategies, reflecting the two opposite extreme matching situations in NZEB; load-matching priority and energy export priority strategies, the model is generic and can be used for hybrid micro-generation options.

4. The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions (original publication IV and V)

4.1 Objective

This study investigates the economic viability of small-scale, multi-generation systems (combined heat and power (CHP), combined cooling, heating, and power (CCHP)), along with conventional heating and cooling systems combining sixteen heating/cooling energy generation systems (H/C-EGSs). The Energy Performance of Buildings Directive (EBPD) comparative framework methodology is followed. The local cost-optimal solution for an office building, in Helsinki, Finland is determined for each H/C-EGS as well as the global cost-optimum. The nZEB and NZEB are also investigated by extending the local cost optimal and minimum energy performance solutions for all H/C-EGSs using a photovoltaic panel system.

4.2 Methodology

In this study, to find the local cost-optimal levels, as well as the global cost-optimal level for the implemented heating/cooling energy generation system packages (H/C-EGSs) serving all considered building energy efficiency measure (EEM) combinations, the steps of cost-optimal framework methodology explained in the EU supplementary EPBD recast [41] are followed. Figure 21 shows in detail the layout of the methodology used to achieve the objectives of this study. In step 1, the reference office building is defined. In step 2, the proposed building EEM are defined and all building EEM combinations are simulated. In step 3, the delivered energies for all combinations are calculated using post-processing of the annual heating, cooling and electrical demands considering the distribution efficiencies, as well as the annual heating and cooling average efficiencies. In step 4, the primary energy (PE) consumption is calculated based on a national conversion of primary factors. Additionally in original publication IV, the CO_2-eq emissions is evaluated based on CO_2-eq emission factors. The associated costs of delivered energies, of a building's EEM investment, heating and cooling systems, replacement, operation and maintenance (O&M), and finally, the total incremental life-cycle cost (dLCC) are calculated. In step 5, the cost-optimal solution and the minimum energy performance solution regarding each H/C-EGS, as well as the global cost-optimal solution are determined.

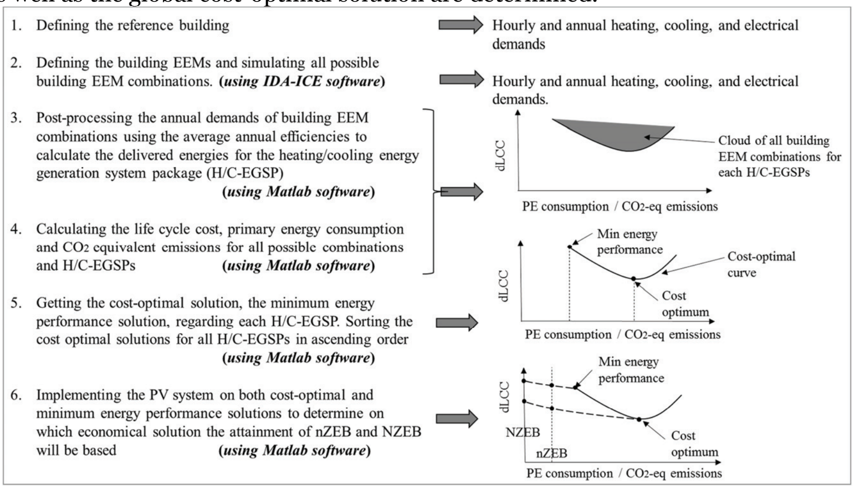

Figure 21 Schematic diagram for the layout of the methodology. (Original publication IV)

According to the EPBD comparative methodology framework [41], the life-cycle cost (LCC) calculation is the method used to assess the viability of building performance. The LCC is the sum of the present value of the investment and discounted operational costs of the building and services systems, including those related to maintenance and replacement, including taxes, over a specified calculation period. In both original publications IV and V, the total incremental life-cycle cost (dLCC) is calculated and presented as a difference cost between each H/C-EGS and a defined reference case which consists of the reference building served by certain H/C- EGS, as given by Eq. (28). The LCC calculation follows a financial cost calculation concerning individual owner perspective [41]. The life-span for office buildings is 20 years as recommended by the EU supplementary EPBD recast [41]. The LCC calculation is illustrated in ANNEX 1 of the supplementary EPBD recast [41].

$$dLCC(\tau) = LCC - LCC_{ref} \tag{28}$$

The nearly zero-energy building (nZEB) was defined earlier in Section 1.1. Finland has not yet announced an official nZEB definition. However, it can be assumed that the nZEB requirement is the highest energy efficient class according to the current Finnish regulations building energy certificate [69]. Therefore, for office buildings, the highest energy efficient class is "A" where the imported PE has to be less than 80 KWh/m²a. Similarly to the cost-optimal calculation, the nZEB performance is addressed by the imported PE following the energy performance calculation method in [69]. The net zero-energy building (NZEB) is defined as given in Section 1.2.

The nZEB and NZEB can be achieved without installing any supplementary on-site renewable energy generation system as shown by a biomass-based IFGT system with NZEB-Finnish emission in Section 2.7. In this study with NZEB-Finnish PE, the photovoltaic panel (PV) system is chosen as RET to be implemented in the office building (step 6- Figure 21). Therefore, the electricity produced via PV can be utilized for the electrical demand to reduce the energy cost of electricity and the surplus electricity can be exported to the grid for compensating the imported energies and to make financial profits. As shown in step 6 in Figure 21, the PV panels are installed in both the local cost-optimal and minimum energy performance solutions for each H/C-EGSs. The aim is to investigate the economic viability of achieving the nZEB and NZEB based on both solutions and comparing them. However, in original publication V, only the NZEB is investigated by extending the local cost-optimal and minimum energy performance solutions for each H/C-EGS.

4.3 An office building as a case study

4.3.1 Reference building description

The office building is the representative office building identified in [42] located in Helsinki, Finland. It is a six-story office building with a narrow shape (an approximately 50 m x 22 m footprint) with the short sides oriented to the east and the west. Room height is 3.6 m. Each floor is 936 m² and the net heated floor area is 5615 m². Envelope properties, operation schedule, and set point temperatures of the reference office building are shown in Table 11. More detailed descriptions are presented in original publication IV, V and [42]. The reference building and all building EEM combinations are simulated using IDA-ICE 4.5 simulation software [63] using reference year weather data (Vantaa TRY2012) [70] used as well in [42]. Figure 22 shows a plan for the typical floor and building model in a simulation program. The simulation annual demands of the reference building are 21.7 kWh/m²a annual space heating (SPH), 39.3 kWh/m²a ventilation heating, 4.6 kWh/m²a space cooling (SPC), 4.3 kWh/m²a ventilation cooling, and 6.0 kWh/m²a DHW. The electrical demands are 22.3 kWh/m²a lighting, 22.3 kWh/m²a appliances, and 13.3 kWh/m²a HVAC auxiliaries (which includes fan power, but not the electricity used for direct or indirect heating and cooling).

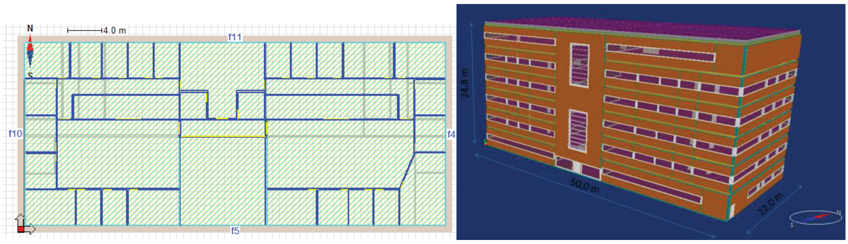

Figure 22 Typical floor plan and the 3D model in IDA ICE of the simulated reference office building. (Original publication IV)

Table 11 Envelope properties, operation schedules, and set points of the reference office building [42]. (Original publication IV)

Property description	***Value***
U-value of walls	0.17 W/m^2K
U-value of roof	0.09 W/m^2K
U-value of ground floor	0.16 W/m^2K
U-value of windows	1.0 W/m^2K
SHGC of Glazing factor	0.68 (-)
Overall window to wall ratio	27.2 %
Infiltration rate (air change per hour)	0.94 (50 Pa) 1/h
Occupancy schedule	Weekdays 07:00 - 18:00 [a]
Lighting schedule and control	Weekdays 07:00 - 18:00 [a]
Appliances schedule and control	Weekdays 07:00 - 18:00 [a]
Ventilation schedules and control	Weekdays 06:00 - 19:00 [a] at other times 0.15 l/sm^2
Heating set point temperature	21 °C
Cooling set point temperature	25 °C
Heating system	Always On
Cooling system	Always On

[a] All detailed profiles depend on the zones utilization, for example, offices, meeting rooms, etc. [42].

4.3.2 Energy efficiency measures (EEM) and packages

In both original publication IV and V, 143 building EEM combinations are proposed to improve the energy performance of the pre-defined reference office building. The building alternatives of EEMs include three levels of wall insulation, four different window types, four levels of infiltration, and three options of BSSP, and their associated costs are presented in Appendix A. More details can be found in original publication IV and V. All 144 building EEM combinations including both building envelope measures and building service system package (BSSP) options are integrated into the simulation software to find out the annual heating, cooling and electrical demands.

Sixteen H/C-EGSs (Table 12) investigated with 144 building EEM combinations yield altogether 2304 cases in original publication IV. Appendix B shows the detailed costs of all investigated H/C-EGSs. The H/C-EGSs are eliminated to seven in original publication V, and yield 1008 cases. The H/C-EGSs are selected to compare between conventional systems and other systems based on small-scale CHP and CCHP technologies. The technical and economic characteristics of all H/C-EGSs are illustrated in detail in original publication IV and V.

Table 12 Heating/cooling energy generation system packages (H/C-EGSs). (Original publication IV)

Heating/cooling energy generation system package (H/C-EGS) description	Abbreviation	Investigated in publication
District heating and vapor compression refrigeration system	DH-VCR	IV, V
District heating and district cooling systems	DH-DC	IV, V
Pellet boiler and vapor compression refrigeration system	PB-VCR	IV, V
Ground source heat pump and free ground cooling	GSHP-GC	IV
Biomass-based organic Rankine cycle and vapor compression refrigeration system	ORC-VCR	IV, V
Biomass-based internal combustion engine with gasifier and vapor compression refrigeration system	ICE-VCR	IV, V
Biomass-based indirect fire gas turbine and vapor compression refrigeration system	IFGT-VCR	IV, V
Biomass-based updraft gasifier with Stirling engine and vapor compression refrigeration system	SE-VCR	IV, V
Pellet boiler and absorption chiller system	PB-AC	IV
Biomass-based organic Rankine cycle and absorption chiller system	ORC-AC	IV
Biomass-based internal combustion engine with gasifier and absorption chiller system	ICE-AC	IV
Biomass-based indirect fire gas turbine and absorption chiller system	IFGT-AC	IV
Biomass-based updraft gasifier with Stirling engine and absorption chiller system	SE-AC	IV
Natural gas-based internal combustion engine and vapor compression refrigeration system	NG-ICE-VCR	IV
Natural gas-based micro-turbine and vapor compression refrigeration system	NG-mT-VCR	IV
Diesel-based internal combustion engine and vapor compression refrigeration system	D-ICE-VCR	IV

In original publication IV, the thermal heating and cooling capacities of all heating and cooling systems vary from building combination to another to cover the peak thermal heat demands for each. Also, the capacities of biomass-based CCHP are sized to cover the total peak thermal heating demand required for heating and cooling purposes [71]. In original publication V, the investigated biomass-based CHPs' capacities are optimized. For the GSHP-GC, the borehole lengths required for both heating and free ground cooling purposes of the 144 building combinations are calculated and optimized using EED 3 (Earth Energy Designer) software [72]. All heating and cooling systems have a life span of 20 years. Therefore, there is no replacement for any heating or cooling system. All CHPs are operated to track the thermal demands with ON/OFF operation using the dead band of a water storage system with a capacity of 3.0 cubic meters. The same control strategy was used in original publication I. In this study, there is only one value for the annual costs including the subscription fees, as well as operation and maintenance (O&M) fees.

The reference office building has EEMs of wall 1, win 1, inf 1, BSSP 1. The reference case consists of the reference building served by DH-VCR as H/C-EGS. The DH-VCR is selected because in the urban area of the Helsinki region, the DH utilized in the building stock has the highest percentage, which is 85% [73]. In [42], only the VCR system was investigated as a cooling option for the new office buildings. The DC option has been growing rapidly in the Helsinki region but it is still not a common cooling option [74].

4.3.3 Energy performance factors and life-cycle cost parameters

The energy performance is commonly defined by PE consumption. Therefore, the national Finnish conversion PE factors and are given in Table 13.

Table 13 Energy carriers' primary energy factors. (Original publication IV)

Energy carrier	Electricity	DH	DC	Pellets	NG	Diesel oil
Primary energy factor kWh_{pe}/kWh	1.7	0.7	0.4	0.5	1.0	1.0

The starting year of the cost calculation is 2013. All costs taken from references before 2013 are updated based on building cost indices and inflation rates from [75]. The calculation period is 20 years. For the basic calculations, a 3% real discount rate is used [41]. The sensitivity analysis is carried out with three different real discount rates of 1%, 6%, and 10%. All building EEMs have a life span equal to the calculation period. Therefore, the residual value will equal zero for all EEMs and packages. No disposal costs for building elements and EEMs are taken into consideration. Table 14 shows the fuel and energy prices and their escalation rates obtained from [76]. All energy prices include taxes and transportation costs.

Table 14 Energy and fuel prices and their escalation rates. (Original publication IV)

Energy carrier	Price (c/kWh)	Escalation rate (%)
Electricity	15.480	2.74%
DH	7.967	1.78%
DC	2.600	1.78%
Pellets	5.600	1.54%
NG	6.597	6.50%
Diesel	11.290	4.42%

Regarding the exported electricity produced by multi-generation systems, the current Finnish energy policy for the feed-in tariff states that the exported electricity produced via new small scale biomass- and biogas-based CHP has a target price of 83.5 €/MWh [77] where the Energy Market Authority will pay the difference between the target price and the average spot market price every three months. This feed-in tariff scheme is applied for twelve years. In light of that, it is assumed that for all CHP technologies including the fossil fuel-based, the exported electricity price is 83.5 €/MWh without taking into consideration any inflation rate over the calculation period.

4.3.4 Implementing PV panels to achieve nZEB and NZEB

According to the offer provided by the local energy distribution companies Fortum Company [78] and Helsingin Energia [79] in the Helsinki region, the PV system is installed completely by those companies and they give fees for purchasing the surplus electricity. Based on the offered PV system by [78], the installation price of the whole PV system is 427.6 €/m^2 (including VAT) with a 20-year guarantee. The annual service fee is 46.70 €. In this study, the hourly electricity produced by the PV system is calculated by TRNSYS 17.1 software [80] according to its specifications [81] using the same reference year's weather data (Vantaa TRY2012) [70]. The orientation of the PV modules is selected to be horizontal instead of the optimal orientation shown in Section 2.6 to utilize the whole roof area without losing in-between areas when the PV modules are tilted, in order to avoid them shading effect on each other. Therefore, the maximum collected solar energy can be acquired. The calculated electricity production after the inverter of one square meter of PV is 119.6 kWh/a. The hourly matching between the electrical demand and the electricity produced via the PV system is carried out using Matlab software.

The exported price of the electricity produced via the PV system varies hourly depending on the spot market price. It is assumed to be equal to the spot market price minus a 0.24 c/kWh margin fee and a 0.07 c/kWh online service fee [78]. The hourly and annual average spot market prices of 2013 are from Nord pool [82]. The average price of 41.16 €/MWh is used. It is assumed that the electricity produced via PV has the same escalation rate as the imported electricity.

4.4 Case study results and discussion

4.4.1 Energy demands (original publication IV and V)

Figure 23 shows the impact of implementing the separate aforementioned building EEMs to the reference office building. The reference building has the main EEMs of wall 1, win 1, inf 1, and BSSP 1. The options of EEMs are two wall options (wall 2 and 3), three window types (win 2, 3, and 4), three infiltration levels (inf 2, 3 and 4), and two options of building a service system package (BSSP 2, and 3), (Appendix A) added separately to the reference building. The simulated annual demands are 67 kWh/m^{2}a for heating, 9 kWh/m^{2}a for cooling, and 58 kWh/m^{2}a for electricity. The most efficient package among the separate EEM packages is the BSSP including daylight control, efficient SFP, and variable-air volume (VAV) ventilation system with airflows depending on the CO_2 levels. The energy saving potential is 24% for the SPH, 80% for ventilation heating, 55% for ventilation cooling, 54% for HVAC auxiliary electrical demands with an SFP of 1.8 kW/(m^{3}s) (BSSP 1) and 62% with an SFP of 1.4 kW/(m^{3}s) (BSSP 2), while the SPC demand increases by 185%. The explanation for the increase of the SPC is related to withdrawing the heat released by internal heat and solar gains at night time in the summer (unoccupied time) where the daytime is too long at higher latitudes. Also, the HVAC auxiliary system and the lighting electrical demand decrease by 62% and 8% respectively. Generally speaking, the external wall with low U-value and lower infiltration level than the reference one has a lower heating demand and a higher cooling demand. The window types 2 and 3 reduce the SPC demand by 52 % and increase the SPH demand slightly in respect to the reference building.

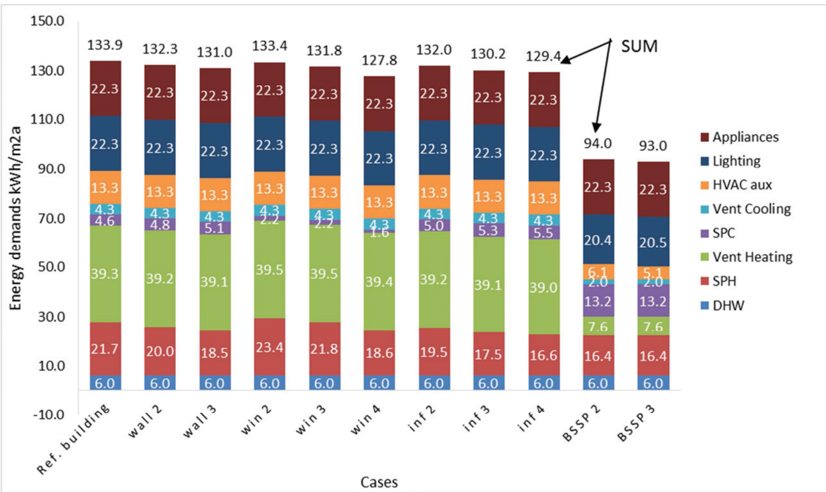

Figure 23 Annual energy demands of the reference building (consists of wall 1, win 1, inf 1, and BSSP 1) and the effect of changing one EEM on the reference building (indicated by EEM changed from the reference case). (Original publication IV and V)

The total annual heating (including DHW, SPH and ventilation heating), cooling (including SPC and ventilation cooling), electrical (including lighting, appliances, and HVAC auxiliaries) demands of the 144 building EEM combinations including the reference building are shown in Figure 24. From this figure, the gap on the X-axis (heating demand) between the two groups of building EEM combinations with BSSP 1 and the other group with BSSP 2 & 3 is due to the large reduction of the SPH demands when the BSSP 2 & 3 are implemented instead of BSSP 1. All building EEM combinations of the BSSP 1 have a constant electrical demand of 57.9 kWh/m^{2}a, while those of BSSP 2 and 3 have approximately the electrical demand of 48.8 kWh/m^{2}a where it varies between 47.8 kWh/m^{2}a and 49.7 kWh/m^{2}a in accordance with the fan power of the ventilation system and the daylight control. It can be concluded that not only for new, but also for retrofitted office buildings, that replacing the CAV system with a VAV system is the most efficient EEM with a formidable saving potential.

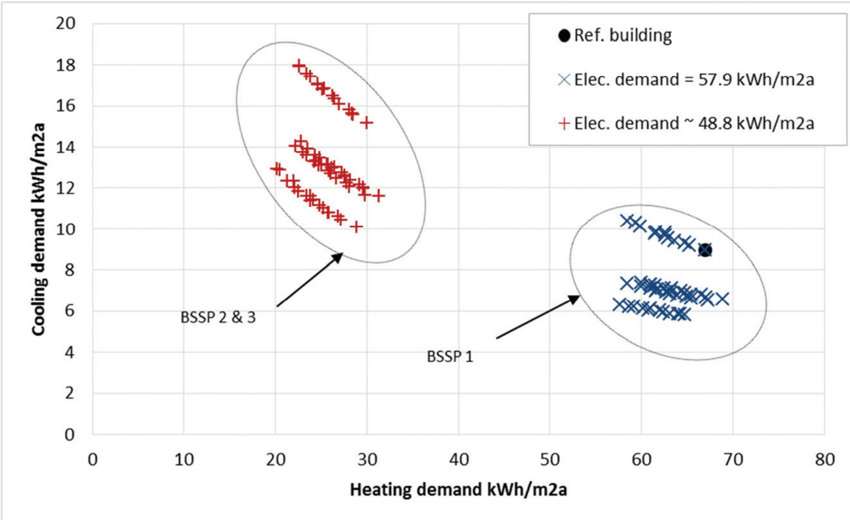

Figure 24 Heating, Cooling, and electrical demands of the 144 building EEM combinations. (Original publication IV and V)

4.4.2 Cost-optimality calculation

Using the financial calculation method, the incremental life-cycle cost is calculated for all cases taking into account the paid costs of the customer including all applicable taxes. The DH-VCR system package serving the reference building is the reference case which has a dLCC equal to 0 €/m² as indicated in Section 4.3.2.

Figure 25 shows the imported PE versus the dLCC of all building EEM combinations served by each H/C-EGS. As shown, for each H/C-EGS, the building EEM combinations are categorized into two groups according to the BSSP options (BSSP 1 and BSSP 2 &3) presented by the filled and unfilled markers, respectively. According to the Finnish building code D3-2012 [32], the imported PE has to be limited to 170 kWh/m²a for new office building. Therefore, the fossil fuel-based CHPs including NG-ICE-VCR, NG-mT-VCR, and D-ICE-VCR with all building combinations of BSSP 1 are not appropriate to be a heating system option due to the high PE factors of NG. Moreover, the biomass-based CHP (ICE-VCR) and CCHP (ICE-AC) with some building combinations of BSSP 1 are not appropriate to be a heating system option as well. This is due to that high amount of pellet fuel that has to be imported as a result of low thermal efficiency of the biomass-based ICE.

The cases of building combinations of BSSP 2&3 with DH-VCR, DH-DC, PB-VCR, and GSHP-GC as conventional H/C-EGSs, PB-AC, ORC-VCR, and SE-VCR have a negative dLCC showing the economic savings in respect to the reference cases. This is due to reducing both the investment cost of H/C-EGSs and the energy cost through the building's life span. Additionally, the cases of BSSP 1 group with PB-VCR and GSHP-GC have also dLCC less than the reference case. The pellet boiler technology, which is a mature product with the advantage of running on an abundance of biomass fuels, requires relatively low investment and annual costs. The pellet fuel price and its escalation rate are the lowest among all energy carriers. The GSHP-GC is a low-operating-cost, environmentally friendly H/C-EGS.

Regarding the multi-generation systems shown in Figure 25, it can be noticed that biomass-based CHP technologies with a high P/H ratio (such as IFGT and ICE) cannot compete with the conventional systems due to the following reasons. The first one is the high investment cost relating to high heating and electrical capacities as well. The second reason is that high P/H ratio, which means low thermal efficiency yields to high operational cost since the CHP operational strategy is thermal tracking. On the contrary, the biomass-based CHP technologies with low a P/H ratio (such as SE and ORC) can compete with the conventional systems.

Regarding the biomass-based CCHP, it can be concluded that it does not have an environmental advantage in respect to the imported PE, while it will be feasible in respect to the net PE consumption. From an economic point of view, the dLCC increases significantly as a result of increase in the investment cost of both biomass-based CHP and the AC as well as the purchased fuel. The same conclusion of the lack of economic viability of a small scale biomass-based CCHP was reached by [83] and [84].

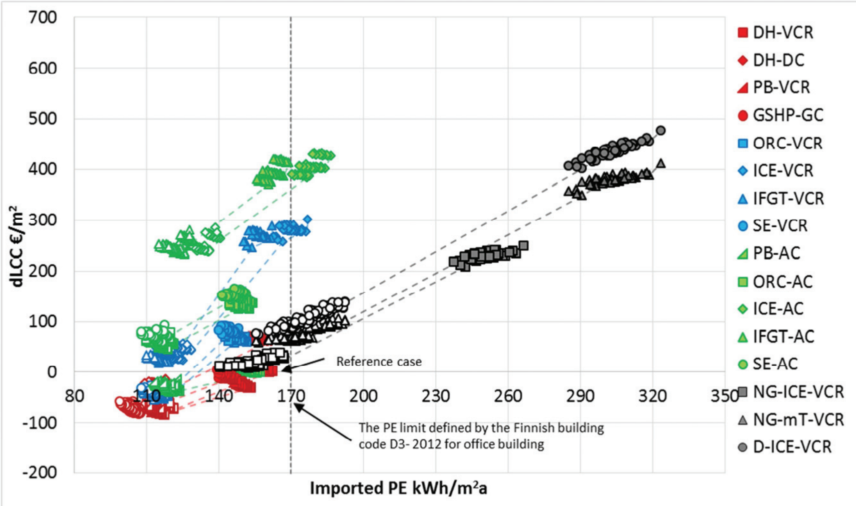

Figure 25 Incremental life-cycle cost (dLCC) versus imported primary energy (PE) for all building EEM combinations integrated with H/C-EGSs. Filled and unfilled markers refer to BSSP 1 and BSSP 2&3 combinations, respectively. The dashed lines link visually between the two groups for each H/C-EGS. (Original publication IV)

Table 15 shows the cost-optimal and minimum energy performance solutions regarding the imported PE for all H/C-EGSs. The reference case has an imported PE of 162.4 kWh/m²a. The global cost-optimal solution belonging to the GSHP-GC has a dLCC of -83 €/m² and an imported PE of 107 kWh/m²a, with an overall savings of 34% with respect to the reference case. Its building EEM combinations are wall 1, win 1, and inf 1 and BSSP 2. The GSHP-GC is a low-operating-cost, environmentally friendly H/C-EGS with high thermal performance (COP coefficient of performance). The PB-VCR has an imported PE of 117 kWh/m²a and dLCC of -82 €/m² due to the abovementioned features of PB technology and low pellet fuels price and escalation rate.

Regarding the multi-generation systems, the ORC-VCR and SE-VCR have the lowest dLCC among all CHP and CCHP systems of -55 €/m² and -49 €/m², respectively, corresponding to an imported PE of 113 kWh/m²a and 112 kWh/m²a. The fossil fuel-based CHP systems record the highest imported PE as well as a relatively high dLCC.

The difference between the dLCC of the global cost-optimal solution of GSHP-GC and that of GH-DC (which has maximum negative incremental life-cycle cost of -36 €/m²) is 47 €/m². Comparing this value with the global cost-optimal (1889 €/m²) given by [42], even though the difference between the life span used in this study (20 years) and that used in [42] (40 years), it is found that it yields less than 2.5 %. Therefore, due to inputs data uncertainty, each of these system combinations GSHP-GC, PB-VCR, DH-VCR, ORC-VCR, SE-VCR, and DH-DC could be the global cost-optimal solution.

As shown in Table 15, the local cost-optimal solutions for all biomass-based CHPs, and NG-ICR-VCR have building EEM combinations of wall 2, win 2, inf 4, and BSSP 2 as the cost effective EEMs for both heating and cooling demands. Once the AC and DC cooling systems are implemented, there is no need to invest more in the infiltration level due to dependency on the lowest energy carriers' costs. Therefore, the DH-DC and all CCHPs have building EEM combinations of wall 2, win 2, inf 1, and BSSP 2. However, for the GSHP-GC, PB-VCR, and DH-VCR which have the lowest dLCC and the highest heating efficiency and/or COP, there is no need to invest more in the building EEMs, only implementing the most efficient EEM (i.e., BSSP 2 & 3) in the reference building. Due to high energy prices of the fossil fuel supplied to the fossil fuel-based CHPs, the local cost-optimal solutions have high levels of the building EEM combinations of wall 2, win 4, inf 4, and BSSP 3 except the NG-ICE-VCR with arelatively low P/H. The minimum energy performance solutions for all H/C-EGSs have the highest EEM levels of wall 3, win 4, inf 4, and BSSP 3.

The investor or the decision maker might not depend only on the results of the comparative framework methodology, where other factors are not reflected in the methodology and/or are excluded in this study. For example, the heating/cooling system package's reliability, social acceptance, local emission, additional space required depending on the footprint, fuel procurement and storage, etc. have a strong influence on the decision making.

Table 15 Local cost-optimal and minimum energy performance solutions (imported PE) and their building EEM combinations for each H/C-EGS, as well as the reference case. The H/C-EGSs are in ascending order according to the dLCC of the cost-optimal solutions. (Original publication IV)

	Local cost-optimal solutions					Minimum energy performance solutions				
	dLCC €/m^2	PE_{imp} kWh/m^{2}a	PE_{Exp} kWh/m^{2}a	EEM [wall, win, inf, BSSP]	PV area to reach NZEB m^2	dLCC €/m^2	PE_{imp} kWh/m^{2}a	PE_{Exp} kWh/m^{2}a	EEM [wall, win, inf, BSSP]	PV area to reach NZEB m^2
Ref. case	0	162	0	[1, 1, 1, 1]	4484	-	-	-	-	-
GSHP-GC	-83	107	0	[1, 1, 1, 2]	2946	-59	99	0	[3, 4, 4, 3]	2733
PB-VCR	-82	117	0	[1, 1, 1, 2]	3233	-62	108	0	[3, 4, 4, 3]	2971
DH-VCR	-73	121	0	[1, 1, 1, 2]	3347	-58	110	0	[3, 4, 4, 3]	3047
ORC-VCR	-55	113	6	[2, 2, 4, 2]	3127	-37	109	5	[3, 4, 4, 3]	3000
SE-VCR	-49	112	8	[2, 2, 4, 2]	3101	-32	108	6	[3, 4, 4, 3]	2977
PB-AC	-39	121	0	[2, 2, 1, 2]	3330	-19	113	0	[3, 4, 4, 3]	3116
DH-DC	-36	119	0	[2, 2, 1, 2]	3280	-22	109	0	[3, 4, 4, 3]	3016
NG-ICE-VCR	7	153	20	[2, 2, 4, 2]	4212	12	140	16	[3, 4, 4, 3]	3870
IFGT-VCR	16	115	17	[2, 2, 4, 2]	3183	33	110	14	[3, 4, 4, 3]	3033
ICE-VCR	22	121	17	[2, 2, 4, 2]	3332	49	114	14	[3, 4, 4, 3]	3154
ORC-AC	45	119	10	[2, 2, 1, 2]	3283	65	110	7	[3, 4, 4, 3]	3036
NG-mT-VCR	59	157	31	[2, 4, 4, 3]	4321	62	156	30	[3, 4, 4, 3]	4297
SE-AC	59	117	12	[2, 2, 1, 2]	3224	79	108	9	[3, 4, 4, 3]	2981
D-ICE-VCR	74	157	26	[2, 4, 4, 3]	4322	77	156	25	[3, 4, 4, 3]	4297
IFGT-AC	232	126	34	[2, 2, 1, 2]	3474	251	115	26	[3, 4, 4, 3]	3183
ICE-AC	237	136	34	[2, 2, 1, 2]	3755	252	124	26	[3, 4, 4, 3]	3416

4.4.3 nZEB and NZEB calculations

In the context of the aforementioned nZEB and NZEB definitions, PV as a RET is implemented to reach nZEB and NZEB. As shown in Figure 26, the PV system in a 200 m² module step is installed “onsite” reaching 1000 m², which is approximately equal to the roof area of the office building, while a PV system over 1000 m²; it has to be installed “nearby”. The local cost-optimal solutions for all H/C-EGSs are extended by installing a PV area equal to the maximum PV area determined to achieve the NZEB balance between the imported and exported PE as given in Table 15. It can be noticed that a PV area ≤ 1000 m² has a small increase in the dLCC. The reason is primarily related to the high correlation between the PV electricity production and the electrical demand. The percentage of the onsite utilized electricity varies between 65% and 72% depending on the H/C-EGS. However, a small addition LCC is observed as the difference between both the investment cost of a PV system and the exported electricity and the annual cost savings of the imported electricity. Over a 1000 m² PV area, where the

PV area has to be installed nearby, the percentage of onsite utilized electricity produced by the PV system decreases and the dLCC increases rapidly due to the low feed-in tariff of the exported electricity. The dLCC of the extended local cost-optimal solutions by a PV system are less than those of the extended minimum energy performance solutions as presented by the GSHP-GC. Therefore, the NZEB balance is fulfilled and presented as the local cost-optimal solutions of each H/C-EGS.

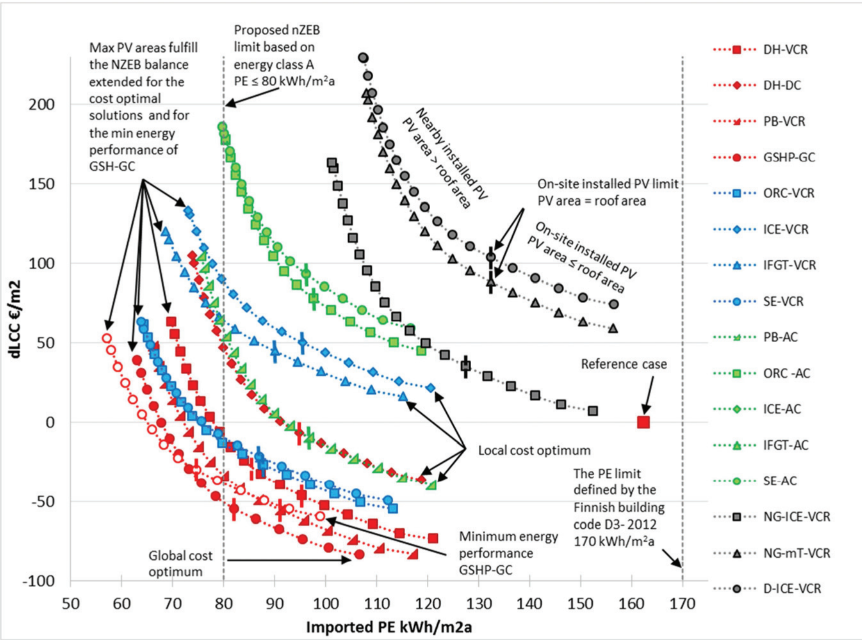

Figure 26 The incremental life-cycle cost of implementing a PV system in 200 m^2 modules versus the imported PE for the local cost-optimal solutions of each H/C-EGS. The GSHP-GC has two extensions based on local cost-optimal (filled marker) and minimum energy performance solutions (unfilled marker). The IFGT-AC and ICE-AC are out of the dLCC range. The EEM combinations and maximum PV area achieving the NZEB are given in Table 15. (Original publication IV)

4.4.4 Sensitivity analysis

The sensitivity analysis was carried out to show the effect of different real discount rates on the local cost-optimal solutions for all H/C-EGSs. The basic real discount rate used as aforementioned is 3%. The other three real different discount rates are: 1%, 6%, and 10%. Figure 27 shows the imported PE and dLCC of the local cost-optimal solutions where the H/C-EGSs are in ascending order based on their dLCC of the base calculation of 3% of the real discount rate. The dLCC is calculated relative to its reference case cost with the same real discount rate, therefore the costs of reference cases with all real discount rates are drawn on zero value. The change of the imported PE for the same H/C-EGSs with different real discount rates means a change in its cost-optimal solutions' building EEM combinations. It can be concluded that, the GSHP-GC is a global cost optimal solution with low real discount rates of 1% and 3%. The DH-VCR and PB-VCR become the global cost-optimal solutions, with 6% and 10% real discount rates, respectively. The DH-VCR and DH-DC become more economic than the ORC-VCR and SE-VCR with high real discount rates of 6% and 10%. All biomass-based CCHPs are the most expensive system packages with high real discount rates of 6% and 10%. Natural gas and diesel oil have high energy costs and high escalation rates. Therefore the discounted annual costs of fossil fuel are decreased significantly compared to other energies when the real discount factors increases. Additionally, increasing the imported PE of 6% and 10% real discount rates cases yields that the dLCCs are close together for all studied real discount rates.

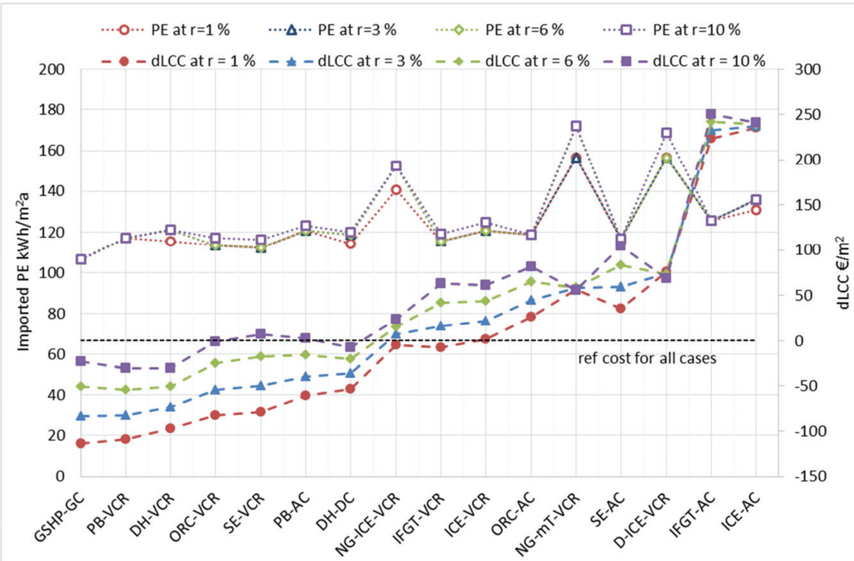

Figure 27 The cost-optimal solutions versus the imported PE consumption for each heating/cooling system package at different discount rates. The H/C-EGSs are in ascending order according to the cost-optimal solutions obtained from base calculation with a 3% discount rate. (Original publication IV)

4.5 Effect of optimizing the biomass-based CHP's capacity on the cost optimal results (Original publication V)

In original publication IV, the multi-generation systems including the CHP and the CCHP systems are sized to cover the total peak thermal heating demand required for both heating and cooling purposes, respectively. Original publication V aims at investigating whether the results of original publication IV will be changed or not if the small scale biomass-based CHP system capacity is optimally sized to be a ratio of the thermal peak demand, while the remaining heating thermal demand can be covered by an auxiliary pellet boiler. It was concluded from original publication IV that the PB-VCR system was ranked as the second cost optimal solution because the PB technology is a mature product and has relatively low investment and annual costs. Moreover, pellet fuel prices and their escalation rate are the lowest among all energy carriers. In original publication V, the GSHP-GC, all biomass-based CCHP, and fossil fuel-based CHP are excluded.

4.6 Optimizing the biomass-based CHP's capacity

The same methodology as presented in Section 4.2 is followed as well as same the office building, and EEMs. Instead of investigating sixteen H/C-EGSs, only seven are included in this study after excluding the GSHP-GC, all CCHP, and fossil fuel-based CHP.

The CHPs are operated to track thermal demands with ON/OFF operation using the dead band of a water storage system with a capacity of 3.0 cubic meters. The CHPs are the main heating energy generation system and it has the priority to run over the auxiliary PB. The CHP capacities are optimized where the dLCC is reduced without any significant increase in the net PE. The optimized small scale CHP capacity is constrained to be not less than the minimum defined capacity of a small scale CHP of 30 kWe [85]. Figure 28 shows an example of the optimization process of selecting the biomass-based SE and PB capacities with two different building combinations regarding BSSP1 and BSSP 2. The CHP ranges for all CHP technologies are given in Table 16. The capacities and costs of the auxiliary pellet boilers are given in Table 17.

Table 16 CHP technologies' characteristics. (Original publication V)

Pellet-based CHP	**Electric capacity range of CHP covering the peak thermal demand kWe**	**Electric capacity range after optimizing CHP capacity kWe**
ORC	30-90	30-36
ICE	70-225	39-63
IFGT	70-225	38-43
SE	36-108	30-39

Table 17 Pellet boiler ranges and costs. (Original publication V)

Thermal heating capacity kW	**Installation cost €**	**Annual operation and maintenance (O&M) €**
$Q_h < 20$ [a]	5328	300
$20 < Q_h < 30$ [a]	6138	300
$30 < Q_h < 60$ [a]	10676	500
$60 < Q_h < 80$ [a]	11319	700
$80 < Q_h < 200$ [b]	85000	2100
$200 < Q_h < 350$ [b]	100000	2100
$350 < Q_h < 600$ [b]	130000	2100

[a] costs of small pellet boiler capacities are from [86]
[b] costs of larger pellet boiler capacities are from [87]

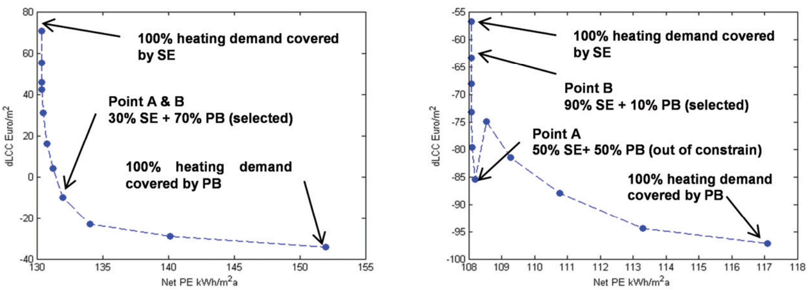

Figure 28 An example for the optimization process of the biomass-based SE capacity and pellet boiler as an auxiliary system. Point A indicates the selected optimal point based on variation of the cost with the net PE. Point B indicates the constrained limit based on minimum capacity of small scale CHP of 30 kWe. Left figure for the reference building with BSSP 1 and the right one with BSSP 2.

4.7 Results of optimizing the CHPs' capacities (original publication V)

Figure 29 shows the cost optimal curves including all solutions which have either minimum dLCC or imported PE when the CHPs' capacities are sized to cover the peak thermal heating energy demand. The solution space has an imported PE in range of 107.6 kWh/m²a and 177.0 kWh/m²a, and the dLCC range of -82.4 €/m² and 306.0 €/m². The PB-VCR has the global cost-optimal solution with a dLCC of -82.4 €/m² and an imported PE of 117 kWh/m²a. Figure 30 shows the local cost-optimal and minimum energy performance solutions for all H/C-EGSs after optimizing the CHP capacities. The solution space is shrunk to be in range of an imported PE of 107.6 kWh/m²a and 161.7 kWh/m²a, and the dLCC range of -82.4 €/m² and 71.8 €/m².

Regarding the biomass-based CHP, both ORC and SE with a low P/H have the lowest dLCC and imported PE as well. This is basically due to considering only the imported energies as a representative energy performance metric while the exported electricity is excluded. Moreover, the generated electricity has relatively low utilized ratio by the electrical demand (≈ 34 % in case of cost-optimal solution of ORC-VCR). The low P/H yields reduce the imported fuel under the operational strategy of thermal tracking. The ICE-VCR system records the highest imported PE and dLCC, while it has the highest exported PE. The effect of optimizing the CHPs' capacities is limited. The local cost optimal solution of SE-VCR becomes less than that of ORC-VCR. Also, the local cost optimal of IFGT-VCR becomes more economic than that of DH-DC. Generally, the investigated small scale biomass-based CHPs with optimal capacities have a cost-optimal solution less than that of the reference case.

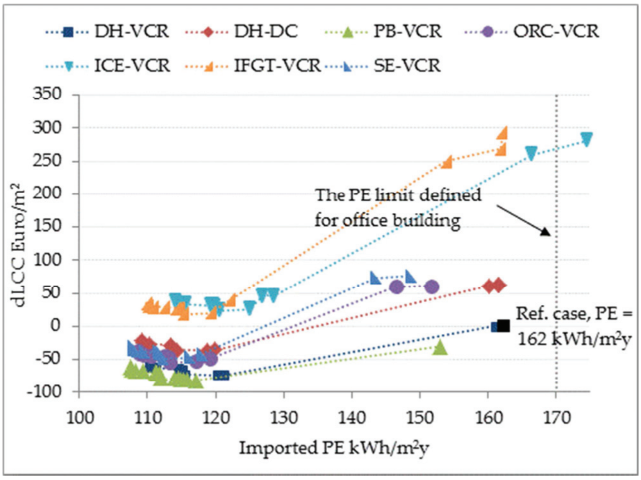

Figure 29 The cost optimal curve for all studied H/C-EGSs. (Original publication V)

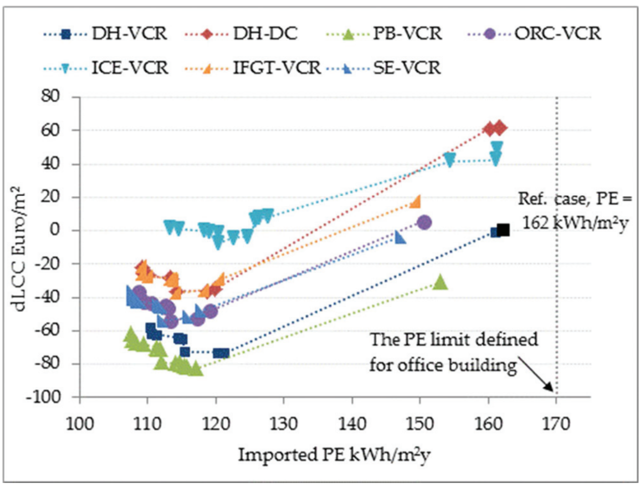

Figure 30 The cost optimal curve for all studied H/C-EGSs after optimizing the CHP capacities. (Original publication V)

4.8 NZEB costs with optimizing the CHPs' capacities

The NZEB calculations are carried out by extending the cost-optimal and minimum energy performance solutions by installing 200 m² as a module step as shown in Figure 31. It can be noticed that the dLCC of the extended local cost-optimal solutions by a PV system are less than those of the extended minimum energy performance solutions. Therefore, the NZEB is achievable with economic viability with slight increase in the dLCC by less than 20 €/m² over the reference case when the cost-optimal solutions are extended by a PV system with PB-VCR, DH-VCR, optimized ORC-VCR, and optimized SE-VCR as an H/C-EGS. Of course, this conclusion helps the policy makers, building's investors, contractors, as well as researchers to identify other barriers facing the NZEB implementation.

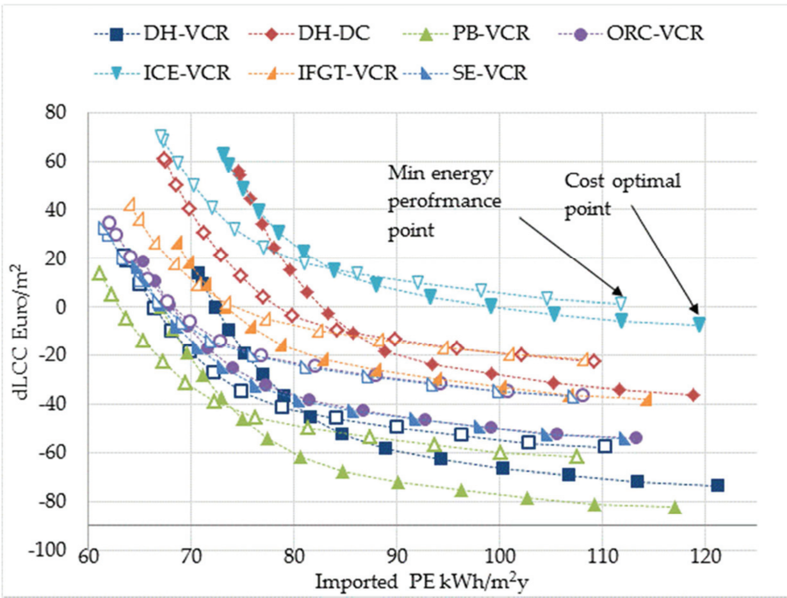

Figure 31 The dLCC of implementing a PV system in 200 m^2 modules versus the imported PE for the local cost-optimal solutions (filled marker) and minimum energy performance solutions (unfilled marker) after optimizing the CHP capacities. (Original publication V)

4.9 Summary

Section 4 was a comprehensive investigation of the economic and environmental viability of small scale biomass- and fossil fuel-based multi-generation technologies serving an office building in Helsinki, Finland. The investigation does not only look at the cost optimal and minimum energy performance solutions but it is extended to analyze nearly and net zero energy office building. The global cost-optimum belongs to the ground source heat pump with free ground cooling. The investigated biomass-based CHPs are economically viable only with high overall efficiency and low P/H ratio due to both low investment and operational costs. The results show also that the biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to the significant increase entailed in both investment and operational costs. The fossil fuel-based CHPs with high operational costs are the worst solutions economically and environmentally. The results show that the ground source heat pump with free ground cooling is the global cost-optimum. The investigated biomass-based CHPs are economically viable only with high overall efficiency and low P/H ratio due to both low investment and operational costs. The biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to the significant increase entailed in both investment and operational costs. The fossil fuel-based CHPs with high operational costs are the worst solution economically and environmentally. Extending the cost optimal solutions by a photovoltaic panel system yields the net zero-energy office building minimum life-cycle costs as well.

5. Conclusion

The net zero energy building (NZEB) has been paid attention to internationally through last decade. Making buildings very energy efficient might be a step toward reaching the NZEB balance but alone it is not sufficient. Integrating the renewable energy systems, hence, is an important step toward achieving NZEB balance as a target. The international efforts carried out on the NZEB definition and surveying the built projects which can be labeled as NZEB projects, do not bring enough information and knowledge that help the decision makers to define the NZEB within the national Finnish circumstances. In the light of that, the NZEB definition and its applicability have been investigated comprehensively in this thesis to cover the most important aspects of the NZEB definition to be defined in consistent way under Finnish circumstances. The investigated aspects include the NZEB balance metric (original publication I), the energy matching capability (original publication II and III), and the economic viability (original publication IV and V). The common factor among these studies is paying more attention to integrated renewable energy systems, especially the multi-generation systems including the micro and small scale, biomass-, and bio syngas-based CHP and biomass- based CCHP technologies given that biomass has the highest renewable energy source share of 25 % in 2013 in Finland. The entire work was done using simulation approach.

Regarding the NZEB definition investigation and its balance metric, the comparison between the four common NZEB definitions: NZEB-PE, NZEB-site, NZEB-emission and NZEB-cost, considering the four metrics of primary energy (PE), site energy, CO_2-eq emissions and energy cost, respectively, using weighting factors based on Finnish and international reference data was conducted. The analysis included five conventional energy systems and seven biomass-based standalone and shared CHP systems connected to a single family house located in Helsinki, Finland. The NZEB definitions can be arranged in the following order according to easiness of achieving the annual balance: (1) NZEB-Finnish emission (2) NZEB-Finnish PE (3) NZEB-cost and (4) NZEB-site reflecting the ratio of the weighting factors of any energy carrier to that of the grid electricity (in this study, the electrical grid is the only two way energy flow considered). Moreover, improving the house thermal energy efficiency for all the studied integrated systems is a step towards achieving NZEB-PE, NZEB-cost, and NZEB-site while that has a reverse effect on the balance achievement of NZEB-Finnish emission for the biomass-based micro and shared CHPs. The local shared biomass CHP systems having better characteristics i.e. high overall efficiency and power to heat ratio (P/H) are up-to-date, better solutions than domestic scale biomass CHP ones from achieving the NZEB balance point of view.

Regarding the energy matching capability, this weighted matching index WMI was proposed based on six extended matching indices which represent six aspects of the matching capability of the assessed on-site electrical, heating, and cooling energy. This WMI was calculated by the sum of six terms, each term being a multiplication of one extended index by a certain weighting factor. The weighting factor represents the preference for a certain aspect of the matching, and the sum of the weighting factors is one. The WMI was implemented to analyze the matching analysis of the μ-CHP units for meeting the electrical and thermal heat demands of a single family house under different scenarios for the weighting factors' relation between each other reflecting various impacts such as the environmental influence, economic benefit, and political decisions. The results showed the influence of weighting factors' selection on the final comprehensive matching results. Thereafter, the question that how can the weighting factors be defined physically and mathematically was answered in the case of μ-CHP operated under thermal and electrical tracking, with and without installing PV and/or STC modules fulfilling the NZEB balance. The weighting factors calculation model was based on the non-renewable primary energy (NRPE) factors (or any other crediting factors like CO_2 emission factor) of the different energy carriers crossing the building boundary. The suggested model was proposed to reflect the two opposite extreme matching situations in NZEB; (i) a load-matching priority strategy (maximizing the load matching), (ii) an energy export priority strategy (maximizing the energy export). However, the model is generic, because it takes into account the energy quality and energy conversion by using NRPE factors (or any other crediting factors like CO_2 emission factor). The importance of the WMI is that it is a quantitative parameter, indicating the overall energy matching situation. Therefore, integrating the energy matching capability to be an objective in a multi-objective optimization calculation for nearly and net ZEB becomes possible.

Regarding the economic viability, the local and global cost optimal solutions were determined in compliance with the Energy Performance of Buildings Directive (EBPD) comparative framework methodology. The analysis includes small-scale multi-generation systems (CHP, combined cooling, heating, and power (CCHP)), along with conventional heating and cooling systems combining sixteen heating/cooling energy generation systems (H/C-EGSs) serving an office building, in Helsinki, Finland. The suggested energy efficiency measures got 144 building combinations, and alongside the H/C-EGSs, altogether 2304 cases. The results showed that the global cost-optimal solution is the ground source heat pump with free ground cooling. The investigated biomass-based CHPs are economically viable only with high overall efficiency and low P/H ratio due to both low investment and operational costs. The results showed also that the biomass-based CCHPs do not have economic or environmental benefits over the biomass-based CHPs due to the significant increase entailed in both investment and operational costs. The fossil fuel-based CHPs with high operational costs are the worst solutions economically and environmentally. Finally, extending the cost optimal solutions by a photovoltaic panel system yields the net zero-energy office building minimum life-cycle costs as well.

Finally, this thesis shows that the bioenergy-based CHP technologies could be a promising integrated renewable energy system in Finland achieving the NZEB based on community level rather than single building level. To achieve the NZEB balance, CHP's characteristics have to be well optimized and selected in order to minimize the dependency on solar energy, to maximize energy matching, and to minimize life cycle cost. The upcoming legislation of nearly and net ZEB has to take the outputs of this thesis into consideration.

6. Future work

To help decision maker in legislation regarding the NZEB under national Finnish circumstances, other NZEB's aspects should be investigated to bring enough information about the influences of implementing the NZEB socially, economically, and environmentally. Some of the NZEB's aspects which could be further investigated are symmetric and asymmetric weighting systems for bi-direction grid networks, the effect of time dependent accounting of the weighting system, using references for weighting factors such as EU standards EN15603, etc. Other building types could be investigated with the NZEB like blocks of flats, hospitals, etc., as well as investigating the technical and economic requirements of deep renovation for existing buildings in order to fulfil the NZEB balance.

Regarding the CHP technologies, the technical considerations of part load performance of the CHP could be further investigated. Different operational strategies could be investigated, such as either the simple operational strategies like thermal and electrical tracking or hybrid operational strategy where operation can be controlled seasonally or monthly or based on an optimization technique aiming at minimizing the economic or environmental performance. The most important investigation is field verification of implementing the CHP technologies by measuring and monitoring a real prototype project.

Regarding the energy matching analysis, it is worthy to conduct sensitivity analysis as well as optimization to investigate the effect of some parameters not considered in this study such as the capacity and other parameters of the storage devices, such as the hot water storage tank or electrical battery. Moreover, it is essential to apply the same methodology of calculating the weighting factors of the WMI with different cases which have cooling demand and are connected to bi-direction cooling thermal grid.

Finally, it is important to integrate the multi-generation technologies such CHP and CCHP into a multi-objective optimization-based simulations to obtain the optimal trade-off relations between conflicting objective functions such as "energy consumption, net primary energy consumption, or CO_2-equivelient emission", "initial cost or life cycle cost", "equipment size", and "energy matching". Future analysis should include not only the operational energy but also the embodied energy of building elements and energy generation systems as well.

Appendix A Energy efficiency measures and their costs

The proposed energy efficiency measures (EEM) included in the computational case study; external wall insulation levels, window types, infiltration levels, and building service system package (BSSP) (ventilation system and daylight control) are listed in Table A. 1, Table A. 2, Table A. 3, Table A. 4, respectively. The references for all items are in Original Publication IV.

Table A. 1 External wall insulation levels and their cost

Wall insulation	Material	Insulation thickness (m)	U-values (W/m^2K)	Investment cost (€/m^3)
Wall 1 Wall 2 Wall 3	Mineral wool	0.24, 0.35, 0.54	0.17, 0.12, 0.09	64

Table A. 2 Window types.

Window no	U-value (W/m^2K)	T-value	SHGC	Cost (€/m^2)	Description
Win 1	1.0	0.56	0.68	250	Triple-laminated glass wood aluminum (Argon gas)
Win 2	1.0	0.34	0.46	258	Triple-laminated glass wood aluminum (Argon gas)
Win 3	0.85	0.29	0.42	290	Quadruple-laminated glass wood aluminum (Krypton gas)
Win 4	0.7	0.2	0.3	350	Quadruple-laminated glass wood aluminum (Krypton gas)

Table A. 3 Infiltration levels.

Infiltration level	Specification n50 (1/h)	Additional labor cost (€/m^2 of envelope)
Inf 1	1.0	0.0
Inf 2	0.74	4.15
Inf 3	0.49	8.3
Inf 4	0.37	9.6

Table A. 4 Building service system packages of ventilation system, daylight control.

System packages	BSSP 1	BSSP 2	BSSP 3
AHU #1			
Heat recovery effectiveness	0.6	0.8	0.8
Maximum allowable exhaust air temperature	4.0	1.0	1.0
Ventilation control	CAV	VAV	VAV
Air flow rates of L/s,m²	1.85	min 0.07 max 1.85	min 0.07 max 1.85
Specific fan power (SFP) kW/(m^3/s)	2	1.8	1.4
AHU #2			
Heat recovery effectiveness	-	0.55	0.55
Maximum allowable exhaust air temperature	4.0	1.0	1.0
Air flow rate (constant flow), L/(s.m²)	0.15	0.15	0.15
Ventilation control	CAV	CAV	CAV
Specific fan power (SFP)	2	1.8	1.4
Total ventilation system cost (€/m²)	90	110	115
Daylight control (Yes/No)	No	Yes	Yes
Building automation cost (€/m²)	10	15	15

Appendix B Heating/cooling energy generation system packages' (H/C-EGS) performance and cost

The H/C-EGSs' performance and costs are shown in Table B. 1-Table B. 5. The references for all items are in Original Publication IV.

Table B. 1 District heating and district cooling costs for business customer.

System	Thermal capacity (kW)	Installation cost (€)	Annual subscription fees (€)
DH	$61 > Q_h > 190$	15500	$22.7\ Q_h + 2753.73$
	$191 > Q_h > 350$	24800	$22.7\ Q_h + 2753.73$
DC	$220 > Q_c > 315$	$372 \times Q_c$	$58.28\ Q_c$

Q_h is thermal heating capacity.
Q_c is thermal cooling capacity.
The fixed annual fees are service and subscription cost.

Table B. 2 Pellet boiler costs.

Thermal heating capacity (kW)	Thermal efficiency (%)	Installation cost (€)	Annual operation and maintenance (O&M) (€)
$100 < Q_h < 200$	84.0	85,000	2,100
$200 < Q_h < 350$	84.0	100,000	2,100
$350 < Q_h < 600$	84.0	130,000	2,100

Table B. 3 GSHP performance and costs.

Item	cost	unit
Boreholes drilling	33.45	€/m
Piping of the ground heat exchanger	15	€/m^2 of gross building area
Heat pump equipment	325	€/kW

Table B. 4 Vapor compression refrigeration (VCR) cooling system and absorption chiller system performance and costs.

System	COP	Installation cost (€)	Annual O&M (€)
Vapor compression refrigeration (VCR) cooling system	3.0	72020	620
Absorption chiller (AC) system	0.7	133578	Every year = 3000 Every 3 years = 50000 After 10 years = 15000

Table B. 5 CHPs technologies' characteristics and costs.

Technologies	**Fuel**	**Electrical efficiency η_e %**	**Thermal efficiency η_{th} %**	**Overall efficiency η_{ov} %**	**Power to heat ratio P_e/H_{th}**	**Life-time (year)**	**Inv. cost (€/ kW_e)**	**Variable O&M (€/kWh_e)**	**Fixed O&M (€/(kW_e a)**	**Electrical capacity range**
ORC	Pellets	14	70	85	0.2	20	6696	0.0072	135	with VCR 30 – 90 kWe with AC 78 – 114 kWe
Gasifier, ICE	Pellets	23	46	70	0.5	20	5987	0.037	147	with VCR 75 – 225 kWe with AC 195 – 285 kWe
Direct combustion IFGT	Pellets	28	56	84	0.5	20	6800	0.024	131	with VCR 75 – 225 kWe with AC 195 – 285 kWe
Updraft gasifier SE	Pellets	18	72	90	0.24	20	7652	0.032	33	with VCR 36 – 108 kWe with AC 94 – 137 kWe
Natural Gas ICE	NG	25.1	44.4	69.5	0.56	20	1436	0.016	20+37.3	with VCR 85 – 254 kWe
Micro-turbine	NG	31	34	65	0.97	20	1946	0.005	60+37.3	with VCR 146 – 427 kWe
Diesel ICE	Diesel	28.4	33.4	61.8	0.85	20	1439	0.016	7	with VCR 129 – 385 kWe

References

[1] A. Mohamed, A. Hasan, K. Sirén, Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives, Applied Energy, 114 (2014) 385-399.

[2] S. Cao, A. Mohamed, A. Hasan, K. Sirén, Energy matching analysis of on-site micro-cogeneration for a single-family house with thermal and electrical tracking strategies, Energy and Buildings, 68, Part A (2014) 351-363.

[3] A. Mohamed, S. Cao, A. Hasan, K. Sirén, Selection of micro-cogeneration for net zero energy buildings (NZEB) using weighted energy matching index, Energy and Buildings, 80, (2014) 490-503.

[4] A. Mohamed, M. Hamdy, A. Hasan, K. Sirén, The performance of small scale multi-generation technologies in achieving cost-optimal and zero-energy office building solutions, Applied Energy, 152C (2015) 94-108.

[5] A. Mohamed, A. Hasan, K. Sirén, Cost optimal and net zero energy office buildings solutions using small scale biomass-based cogeneration technologies, proceedings of Building Simulation Applications - BSA 2015, 2nd IBPSA-Italy Conference, Bozen-Bolzano, Italy. 263-272, ISBN: 978-88-6046-074-5, Bozen-Bolzano University Press. http://bupress.unibz.it/en/buildings-simulation-applications-bsa-2015.html

[6] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on the energy efficiency. Official Journal of the European Union, (2012) 14/11/2012.

[7] EPBD recast, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union, (2010) 18/06/2010.

[8] IEA. SHC Task 40/ECBCS Annex 52, Towards Net Zero Energy Solar Buildings, IEA SHC Task 40 and ECBCS Annex 52, http://task40.iea-shc.org/, 2008 (accessed 30.07.2013).

[9] Torcellini P, Pless S, Deru M. Zero energy buildings: a critical look at the definition. USA: National Renewable Energy Laboratory (NREL); June 2006. http://www.nrel.gov/docs/fy06osti/39833.pdf

[10] I. Sartori, A. Napolitano, K. Voss. Net zero energy buildings: A consistent definition framework. Energy and Buildings 48 (2012) 220–232.

[11] K.F. Fong, C.K. Lee. Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong. Applied Energy 93 (2012) 686–694.

[12] Statistics Finland, Production of electricity and heat. Available at http://www.stat.fi/til/salatuo/2013/salatuo_2013_2014-10-16_kuv_009_en.html (accessed 16.02.2015)
[13] Statistics Finland, Energy Consumption, Available at http://www.stat.fi/til/ehk/2013/ehk_2013_2014-12-10_kuv_001_en.html (accessed 16.02.2015)
[14] A. Aslani, M. Naaranoja, P. Helo, E. Antila, E. Hiltunen, Energy diversification in Finland: achievements and potential of renewable energy development, Int. J. Sustain. Energy. 32 (2013) 504–514.
[15] A. J. Marszal, P. Heiselberg, JS Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano. Zero energy building - a review of definitions and calculation methodologies. Energy and Buildings 43(2011); 4: 971-979.
[16] P. Torcellini, S. Pless, M. Deru. Zero Energy Buildings: A Critical Look at the Definition. National Renewable Energy Laboratory (NREL), USA. June 2006.
[17] Ş. Kılkış. A net-zero building application and its role in exergy-aware local energy strategies for sustainability. Energy Conversion and Management 63 (2012) 208–217.
[18] R. S. Srinivasan, W. W. Braham, D. E. Campbell, C. D. Curcija. Re(De)fining Net Zero Energy: Renewable emergy balance in environmental building design. Building and Environment 47 (2012) 300-315.
[19] L. Wang, J. Gwilliam, P. Jones. Case study of zero energy house design in UK. Energy and Buildings 41 (2009) 1215–1222.
[20] M. Bojic, N. Nikolic, D. Nikolic, J. Skerlic, I. Miletic. Toward a positive-net-energy residential building in Serbian conditions, Applied Energy, 88 (2011), 2407-2419.
[21] W. Y. Saman. Towards zero energy homes down under. Renewable Energy 49 (2013) 211-215.
[22] M. Cellura, F. Guarino, S. Longo, M. Mistretta, Different energy balances for the redesign of nearly net zero energy buildings: An Italian case study, Renewable and Sustainable Energy Reviews. 45 (2015) 100–112. doi:10.1016/j.rser.2015.01.048.
[23] M. Leckner, R. Zmeureanu, Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. Applied Energy 88 (2011) 232–241.
[24] A. J. Marszal, P. Heiselberg. Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. Energy 36 (2011) 5600-5609.
[25] A. J. Marszal, P. Heiselberg, R. L. Jensen, J. Nørgaard. On-site or off-site renewable energy supply systems? Life cycle cost analysis of a Net Zero Energy Building in Denmark. Renewable Energy 44 (2012) 154: 165.
[26] M. Osmani, A. O'Reilly. Feasibility of zero carbon homes in England by 2016: A house builder's perspective. Building and Environment 44 (2009) 1917–1924.
[27] L. Schweber, T. Lees, J. Torriti, Framing evidence: policy design for the zero-carbon home, Building Research & Information. (2015) 1–15. doi:10.1080/09613218.2015.1004658.
[28] N.W. Alnaser, Building Integrated Renewable Energy to Achieve Zero Emission in Bahrain, Energy and Buildings. (2015). doi:10.1016/j.enbuild.2015.01.022.
[29] A. Stefanović, M. Bojić, D. Gordić, Achieving net zero energy cost house from old thermally non-insulated house using photovoltaic panels, Energy and Buildings. 76 (2014) 57–63. doi:10.1016/j.enbuild.2014.02.057.

[30] Department of Communities and Local Government (DCLG). Code for Sustainable Homes: a step change in sustainable home building practice. London: HMSO; 2006.
[31] D3 Finland Code of building Regulation. Energy management in buildings, regulations and guidelines. Helsinki: Ministry of Environment; 2012.
[32] D5 Finland Code of building Regulation. Calculation of power and energy needs for the heating of buildings, guidelines. Helsinki: Ministry of Environment; 2012.
[33] H. Lund, A. Marszal, P. Heiselberg, Zero energy buildings and mismatch compensation factors, Energy and Buildings 43 (2011) 1646–1654. http://dx.doi.org/10.1016/j.enbuild.2011.03.006
[34] K. Voss, I. Sartori, E. Musall, A. Napolitano, S. Geier, M. Hall, B. Karlsson, P. Heiselberg, J. Widen, J.A. Candanedo, P. Torcellini, Load matching and grid interaction of net zero energy buildings, in: Proceedings of EuroSun 2010, Graz, AT, 2010.
[35] J. Salom, J. Widen, J.A. Candanedo, I. Sartori, K. Voss, A. Marszal, Understanding Net Zero Energy Buildings: evaluation of load matching and grid interaction indicators, in: Proceedings of Building Simulation, Sydney, AU, 14–16 November, 2011.
[36] J. Salom, A.J. Marszal, J. Widén, J. Candanedo, K.B. Lindberg, Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data, Applied Energy. 136 (2014) 119–131. doi:10.1016/j.apenergy.2014.09.018.
[37] S. Nielsen, B. Möller, Excess heat production of future net zero energy buildings within district heating areas in Denmark, Energy 48 (2012) 23-31. http://dx.doi.org/10.1016/j.energy.2012.04.012
[38] B. Berggren, J. Widén, B. Karlsson and M. Wall, Evaluation and optimization of a Swedish Net ZEB - Using load matching and grid interaction indicators, in Proceedings of Building Simulation and Optimization, Loughborough, 2012
[39] S. Cao, A. Hasan, K. Sirén, On-site energy matching indices for buildings with energy conversion, storage and hybrid grid connections, Energy and Buildings 64 (2013) 423–438. http://dx.doi.org/10.1016/j.enbuild.2013.05.030
[40] S. Cao, A. Hasan, K. Sirén, Matching analysis for on-site hybrid renewable energy systems of office buildings with extended indices, Applied Energy 113 (2014) 230–247. http://dx.doi.org/10.1016/j.apenergy.2013.07.031
[41] Guidelines accompanying commission delegated regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements, Official Journal of the European Union; 2012
[42] Ministry of the Environment, Finland, Energiatehokkuutta koskevien vähimmäisvaatimusten kustannusoptimaalisten tasojen laskenta-SUOMI. Minimum energy performance requirements for calculating cost-optimal levels-Finland. (in Finnish) http://ec.europa.eu/energy/efficiency/buildings/implementation_en.htm
[43] Jarek Kurnitski, Arto Saari, Targo Kalamees, Mika Vuolle, Jouko Niemelä, Teet Tark. Cost optimal and nearly zero (nZEB) energy performance calculations for

residential buildings with REHVA definition for nZEB national implementation, Energy Build. 43 (2011) 3279–3288. doi:10.1016/j.enbuild.2011.08.033
[44] Mohamed Hamdy, Ala Hasan, Kai Sirén. Optimum design of a house and its HVAC systems using simulation-based optimisation, Int. J. Low-Carbon Technol. 5 (2010) 120–124. doi:10.1093/ijlct/ctq010
[45] Mohamed Hamdy, Ala Hasan, Kai Sirén. Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings, Build. Environ. 46 (2011) 109–123. doi:10.1016/j.buildenv.2010.07.006
[46] Nicolas Pardo, Christian Thiel. Evaluation of several measures to improve the energy efficiency and CO2 emission in the European single-family houses, Energy Build. 49 (2012) 619–630. doi:10.1016/j.enbuild.2012.03.006
[47] Mohamed Hamdy, Ala Hasan, Kai Sirén. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, Energy Build. 56 (2013) 189–203. doi:10.1016/j.enbuild.2012.08.023
[48] M. Palonen, M. Hamdy, A. Hasan, MOBO a new software for multi-objective building performance optimization, in: 13th Conf. Int. Build. Perform. Simul. Assoc, pp. 2567–2574. http://www.ibpsa.org/proceedings/BS2013/p_1489.pdf
[49] G. Han, J. Srebric, E. Enache-Pommer, Variability of optimal solutions for building components based on comprehensive life cycle cost analysis, Energy and Buildings. 79 (2014) 223–231. doi:10.1016/j.enbuild.2013.10.036
[50] V. Corrado, I. Ballarini, S. Paduos, Assessment of Cost-optimal Energy Performance Requirements for the Italian Residential Building Stock, Energy Procedia. 45 (2014) 443–452. doi:10.1016/j.egypro.2014.01.048
[51] B. Wang, X. Xia, J. Zhang, A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings, Energy Build. 77 (2014) 227–235. doi:10.1016/j.enbuild.2014.03.025
[52] B. Güçyeter, H.M. Günaydın, Optimization of an envelope retrofit strategy for an existing office building, Energy Build. 55 (2012) 647–659. doi:10.1016/j.enbuild.2012.09.031
[53] E. Asadi, M.G. da Silva, C.H. Antunes, L. Dias, A multi-objective optimization model for building retrofit strategies using TRNSYS simulations, GenOpt and MATLAB, Build. Environ. 56 (2012) 370–378. doi:10.1016/j.buildenv.2012.04.005
[54] M. Ferrara, E. Fabrizio, J. Virgone, M. Filippi, A simulation-based optimization method for cost-optimal analysis of nearly Zero Energy Buildings, Energy and Buildings. 84 (2014) 442–457. doi:10.1016/j.enbuild.2014.08.031
[55] E. Antipova, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, L. Jiménez, Multi-Objective Optimization coupled with Life-cycle Assessment for Retrofitting Buildings, Energy Build. 82 (2014) 92–99. doi:10.1016/j.enbuild.2014.07.001
[56] E.G. Dascalaki, C.A. Balaras, A.G. Gaglia, K.G. Droutsa, S. Kontoyiannidis, Energy performance of buildings—EPBD in Greece, Energy Policy. 45 (2012) 469–477. doi:10.1016/j.enpol.2012.02.058
[57] N. Ganiç, A.Z. Yılmaz, Adaptation of the cost optimal level calculation method of Directive 2010/31/EU considering the influence of Turkish national factors, Appl. Energy. 123 (2014) 94–107. doi:10.1016/j.apenergy.2014.02.045
[58] R. Hastings. IEA SHC 37 Subtask B: Exemplary Renovation Projects. 2010.
[59] Heljo J, Laine H. Report 2005:2. Sähkölämmitys ja lämpöpumput sähkönkäyttäjinä ja päästöjen aiheuttajina. Suomessa. Näkökulma ja malli sähkönkäytön

aiheuttamien CO2-ekv päästöjen arviointiavarten.Tampere University of Technology. Institute of, Construction Economics [in Finnish].

[60] Statistics Finland. Energy Prices. <http://www.stat.fi/til/ene_en.html>. (accessed 30.07.2013)

[61] Hastings R. IEA SHC 37 Subtask B: Exemplary Renovation Projects; 2010.

[62] RIL 249-2009 Matalaenergiarakentaminen, asuinrakennukset. Suomen Rakennusinsinööri liitto RIL ry (in Finnish).

[63] Solar Energy Laboratory, Univ. of Wisconsin-Madison. TRNSYS 17 - a TRaNsientSYstem Simulation program.2010.

[64] J. Pucker, R. Zwart, G. Jungmeier, Greenhouse gas and energy analysis of substitute natural gas from biomass for space heat, Biomass and Bioenergy 38 (2012) 95-101. http://dx.doi.org/10.1016/j.biombioe.2011.02.040

[65] M. Bianchi, A. De Pascalea, F. Melino, Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application, Applied Energy 112 (2013) 928-938. http://dx.doi.org/10.1016/j.apenergy.2013.01.088

[66] Moritz Schubert, SOLID, "Solar district heating guidelines, Decentral integration of ST in DH systems," 6.2 Decentralized integration of ST in DH networks, SDH Solar district heating, supported by INTELLIGENT ENERGY EUROPE. [Online]. Available: http://www.solar-district-heating.eu/Documents/SDHGuidelinesDiscussionBoard/62DecentralizedintegrationofSTinDHnetworks.aspx

[67] M.A. Rosen, Allocating carbon dioxide emissions from cogeneration systems: descriptions of selected output-based methods, Journal of Cleaner Production 16 (2008) 171-177. http://dx.doi.org/10.1016/j.jclepro.2006.08.025

[68] K. Voss, E. Musall, Net zero energy buildings. International projects of carbon neutrality in buildings. 2nd edition. München: Institut für internationale Architektur-Dokumentation, 2013.

[69] Ministry of the Environment Regulation, the building energy certificate, Ympäristöministeriön asetus, rakennuksen energiatodistuksesta, February 2013. Available at: http://www.finlex.fi/fi/laki/alkup/2013/20130176 (in Finnish).

[70]T. Kalamees, K. Jylhä, H. Tietäväinen, J. Jokisalo, S. Ilomets, R. Hyvönen, et al., Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard, Energy Build. 47 (2012) 53–60. doi:10.1016/j.enbuild.2011.11.031

[71] Y. Huang, Y.D. Wang, S. Rezvani, D.R. McIlveen-Wright, M. Anderson, N.J. Hewitt, Biomass fuelled trigeneration system in selected buildings, Energy Convers. Manag. 52 (2011) 2448–2454. doi:10.1016/j.enconman.2010.12.053

[72] Earth Energy Designer (EED 3) software, http://www.egshpa.com/eed-earth-energy-designer/

[73] City of Helsinki, http://www.hel.fi/hel2/ymk/julkaisut/oppaat/esitteet/teemakatsaus_engl.pdf .

[74] Marko RIIPINEN, Niko WIRGENTIUS, DHC in Helsinki - The Ultimate Heating and Cooling Solution for a Large Urban Area, 2010, available at http://www.worldenergy.org/documents/congresspapers/355.pdf

[75] Statistics Finland, Building cost indices, http://www.stat.fi/til/rki/index_en.html

[76] Statistics Finland, Energy, Energy prices.
<https://www.stat.fi/til/ehi/index_en.html>
[77] Energy Authority, Renewable energy, http://www.energiavirasto.fi/en/web/energy-authority/renewable-energy (Accessed 30.07.2013).
[78] Fortum Company, Fortum.fi (Accessed 30.07.2013).
[79] Helsingin Energia, https://www.helen.fi/ (Accessed 30.07.2013).
[80] Solar Energy Laboratory. Univ. of Wisconsin-Madison. TRNSYS 17 – a TRaNsientSYstem. Simulation program; 2010. http://sel.me.wisc.edu/trnsys/index.html
[81] Naps solar systems http://www.napssystems.com/ (Accessed: June 2013).
[82] Nord pool spot webpage, http://www.nordpoolspot.com/. (Accessed 30.3.2014).
[83] Y. Huang, Y.D. Wang, S. Rezvani, D.R. McIlveen-Wright, M. Anderson, N.J. Hewitt, Biomass fuelled trigeneration system in selected buildings, Energy Convers. Manag. 52 (2011) 2448–2454. doi:10.1016/j.enconman.2010.12.053
[84] Y. Huang, Y.D. Wang, S. Rezvani, D.R. McIlveen-Wright, M. Anderson, J. Mondol, et al., A techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle, Appl. Therm. Eng. 53 (2013) 325–331. doi:10.1016/j.applthermaleng.2012.03.041
[85] R. Beith, Small and Micro Combined Heat and Power (CHP) Systems: Advanced Design, Performance, Materials And Applications, April 201, ISBN: 978-1-84569-795-2. http://www.elsevier.com/books/small-and-micro-combined-heat-and-power-chp-systems/beith/978-1-84569-795-2
[86] Hemeltron, 2013. Hemeltron OÜ [WWW Document]. URL http://www.lvi-viro.fi/
[87] Janfire, 2013. Janfire Company, direct contact.

The net zero energy building (NZEB) has been paid attention to internationally through last decade. Under the Finnish circumstances, there is a lack of knowledge and information that can help decision makers to define the NZEB consistently. In this thesis, some of the most important aspects of the NZEB and its applicability are investigated comprehensively. These aspects are the balance metric, energy matching capability, and economic viability. Integrating renewable energy systems with high efficient energy buildings to fulfill the NZEB balance is inevitable. More attention is paid to micro and small scale multi-generation systems including combined heat and power (CHP) technologies and combined cooling, heating, and power (CCHP). The multi-generation systems provide energy efficiency and environmental benefits due to generating on-site electrical and thermal power for a building simultaneously.

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